The next neutrinoless double beta decay experiment

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IFIC (CSIC & UVEG)

The art of experiment
LBNL, May 2014

Searching for nothing? Rather…

Theoretical introduction

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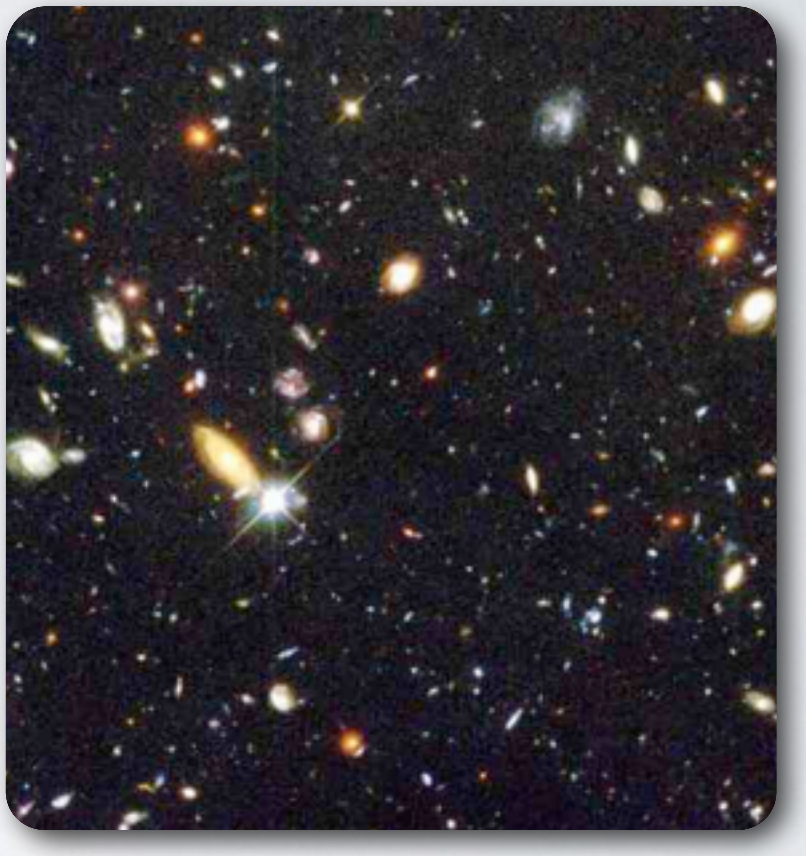
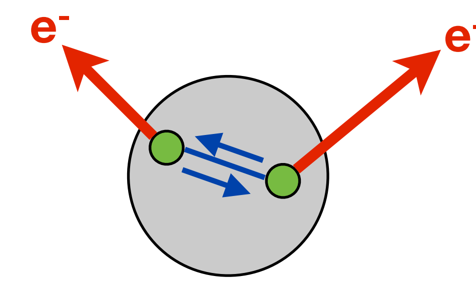
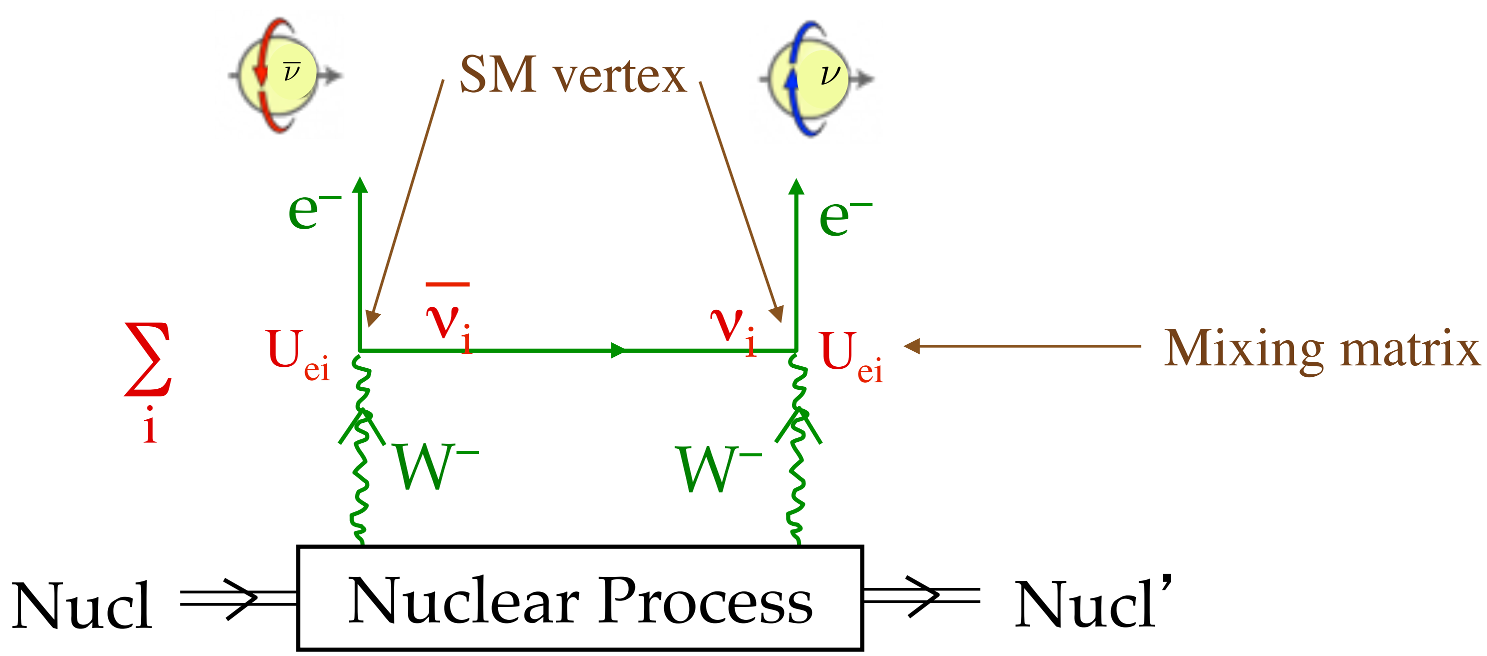


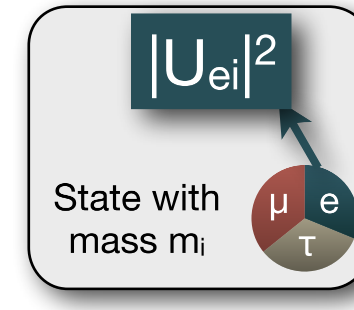
Neutrinoless double beta decay and the neutrino mass

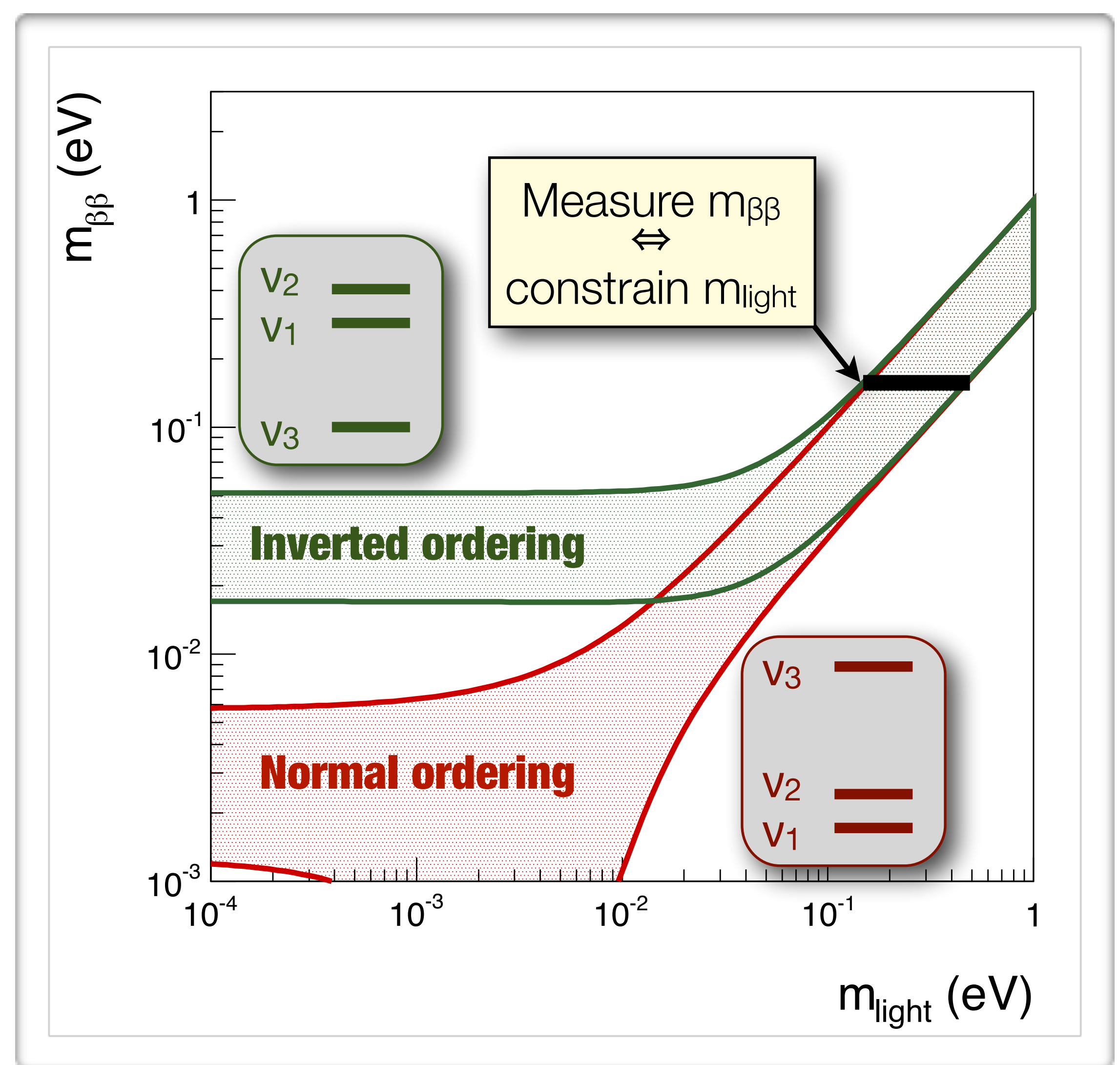




$(\text{Rate})_{\beta\beta0\nu} \propto m_{\beta\beta}^2$

Majorana ν mass:
$m_{\beta\beta} \equiv \left| \sum_i m_i U_{ei}^2 \right|$





→ **helicity flip** $\propto \dfrac{m_i}{E}$

$\mathcal{A} \propto m_i$ **for each** ν_i

Massive neutrinos and cosmology

www.manchester.ac.uk/aboutus/news/display/?id=11555

Massive neutrinos solve a cosmological conundrum

10 Feb 2014

Scientists have solved a major problem with the current standard model of cosmology identified by combining results from the Planck spacecraft and measurements of gravitational lensing in order to deduce the mass of ghostly sub-atomic particles called neutrinos.

The team, from the universities of Manchester and Nottingham, used observations of the Big Bang and the curvature of space-time to accurately measure the mass of these elementary particles for the first time.

The recent Planck spacecraft observations of the Cosmic Microwave Background (CMB) – the fading glow of the Big Bang – highlighted a discrepancy between these cosmological results and the predictions from other types of observations.

The CMB is the oldest light in the Universe, and its study has allowed scientists to accurately measure cosmological parameters, such as the amount of matter in the Universe and its age. But an inconsistency arises when large-scale structures of the Universe, such as the distribution of galaxies, are observed.

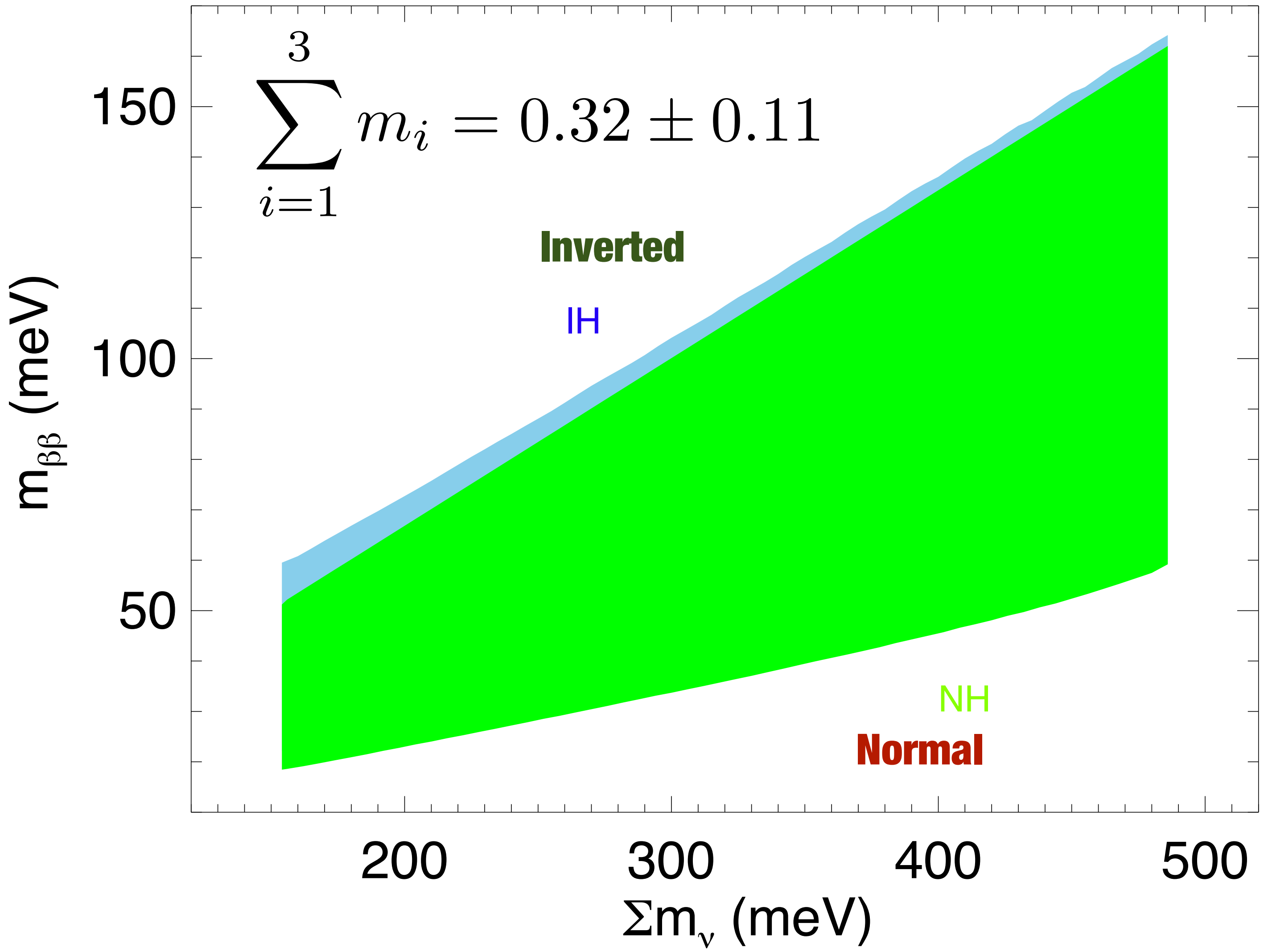
Professor Richard Battye, from the University of Manchester's School of Physics and Astronomy, said: "We observe fewer galaxy clusters than we would expect from the Planck results and there is a weaker signal from gravitational lensing of galaxies than the CMB would suggest.

"A possible way of resolving this discrepancy is for neutrinos to have mass. The effect of these massive neutrinos would be to suppress the growth of dense structures that lead to the formation of clusters of galaxies."

Majorana landscape revisited

Evidence for Massive Neutrinos from Cosmic Microwave Background and Lensing Observations

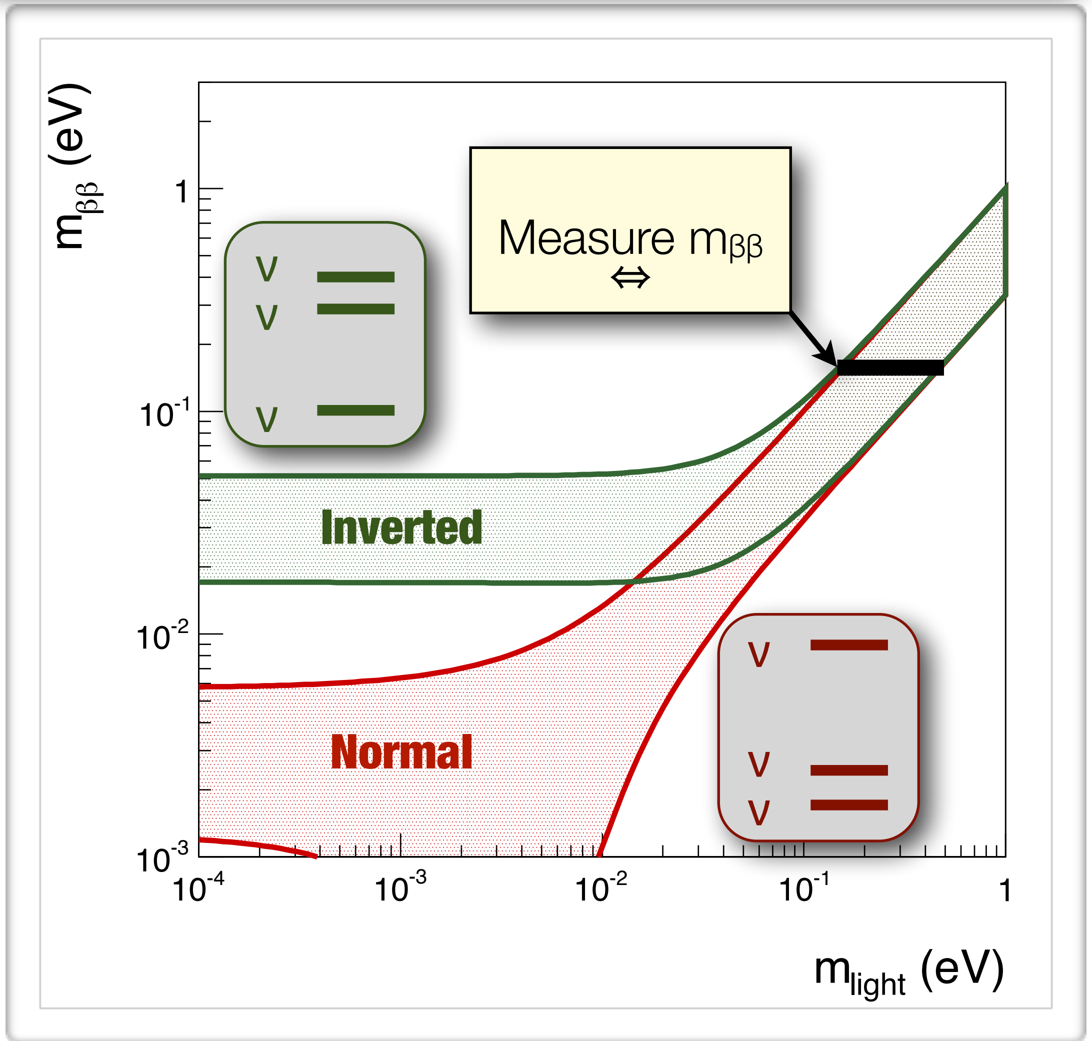
Phys. Rev. Lett. 112, 051303 (2014)



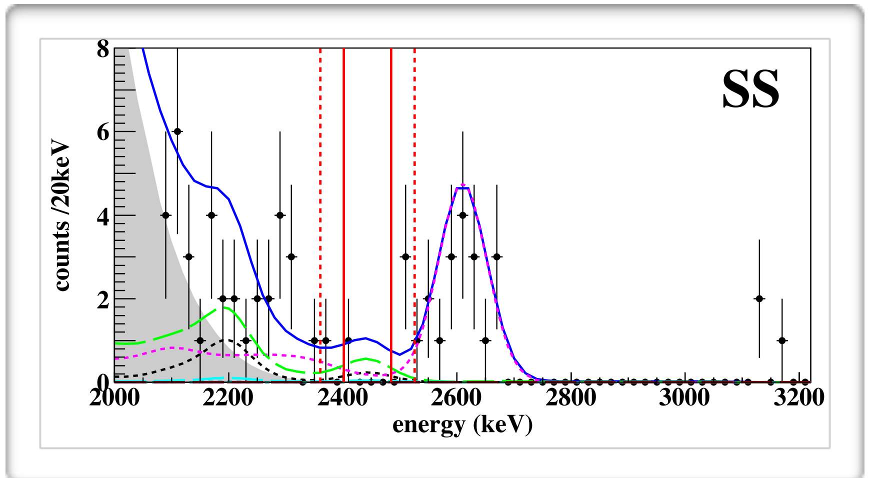
Discovery potential of xenon-based neutrinoless double beta decay experiments in light of small angular scale CMB observations

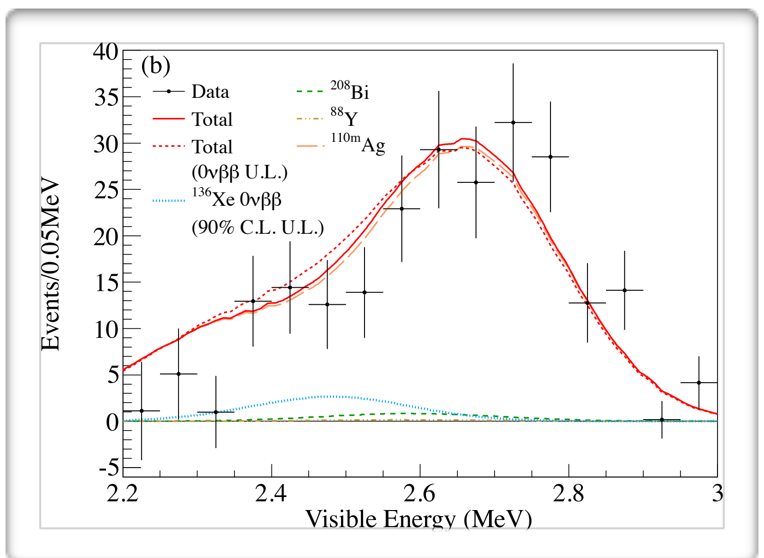
JCAP 1303 (2013) 043

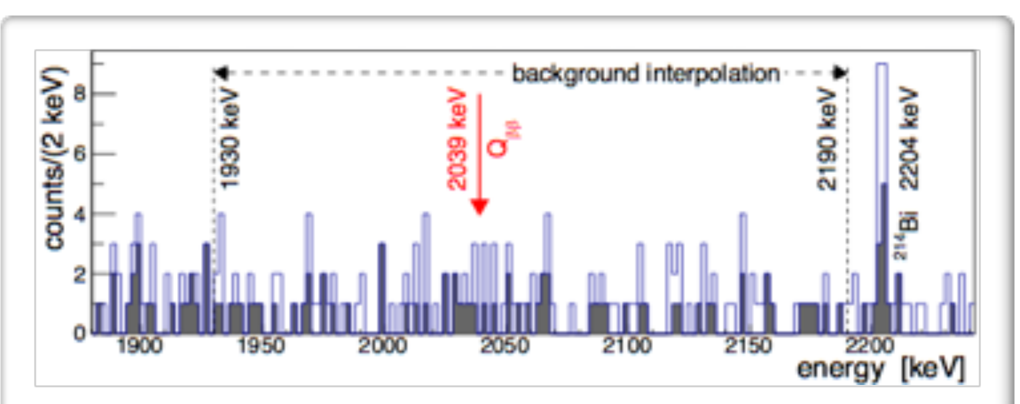
- Discovery window: 15 mev-170 meV
- Bot hierarchies give almost the same "phase space".



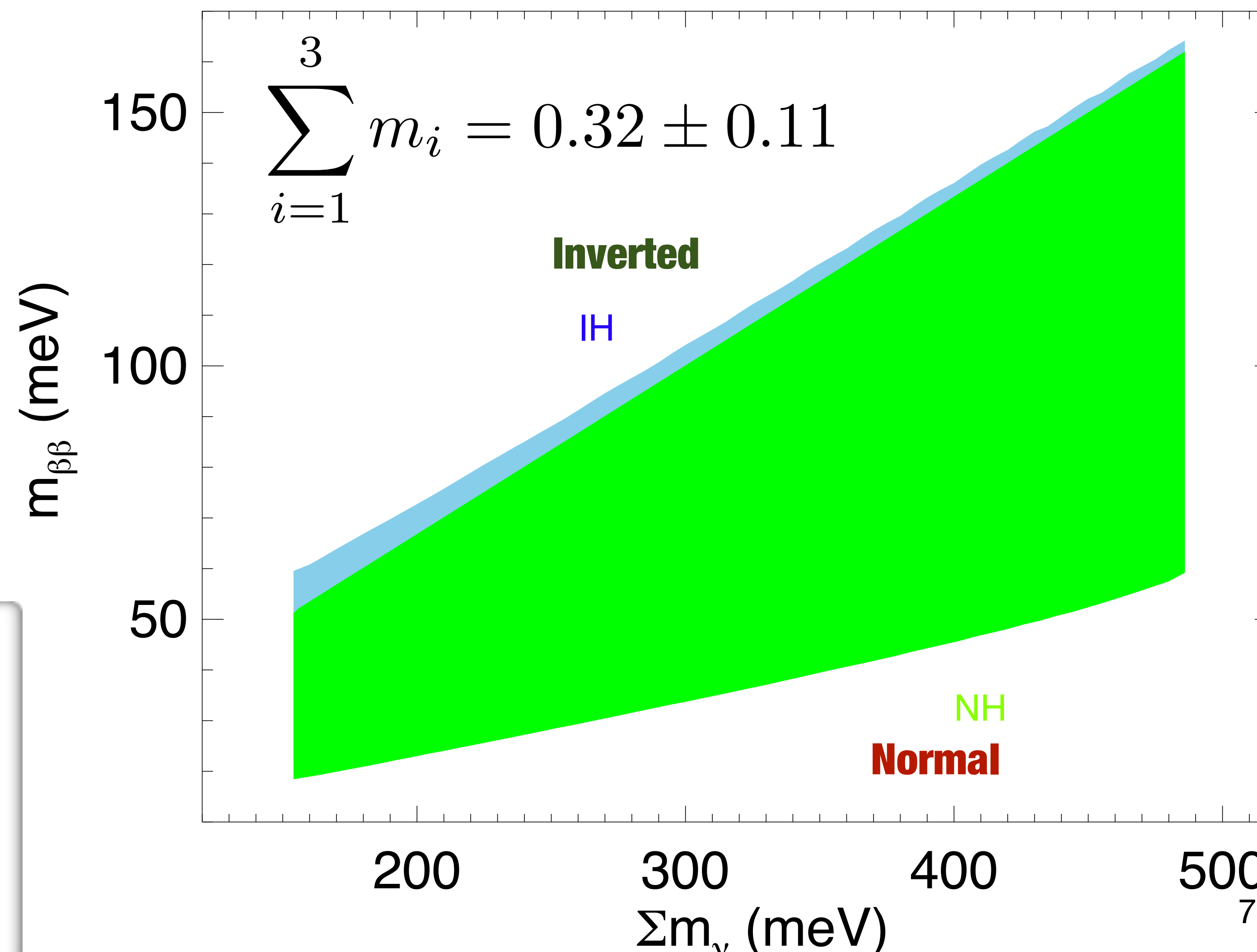
Majorana landscape in 2014





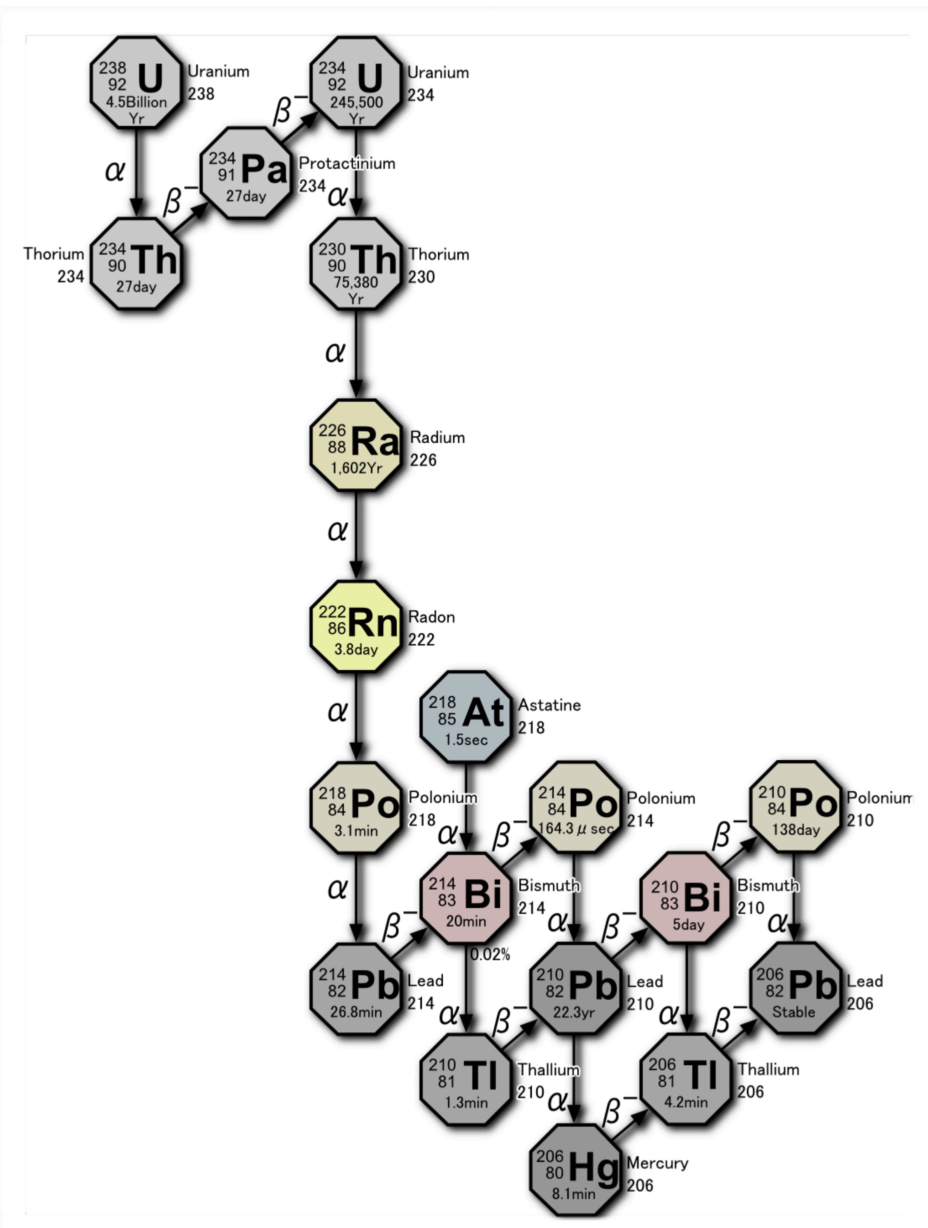


- Claim for ββ0ν strongly disfavored by null results in ^{136}Xe and ^{76}Ge
- $m_{\beta\beta}$ ~ 200 meV.
- Barely out of "cosmo-window"



Experimental challenges

Why ββ0ν experiments are difficult



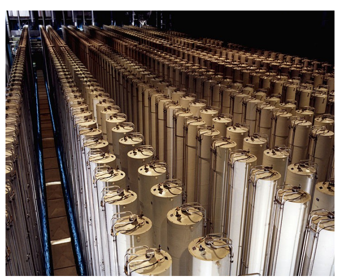
- Earth is a very radioactive planet. There are about 3 grams o U-238 and 9 grams of Th-232 per ton of rock around us.
- This is an intrinsic activity of the order of 60 Bq/kg of U-238 and 90 Bq/kg of Th-232.
- The lifetime of U-238 is of the order of 10^9 y and that of Th-232 10^{10} y. We want to explore lifetimes of of the order of 10^{26} -10^{27} y.

10^{16}: number of sand grains (1mm diameter) in a beach 1 km long, 1km wide, 10 m deep

Building the perfect ββ0ν experiment

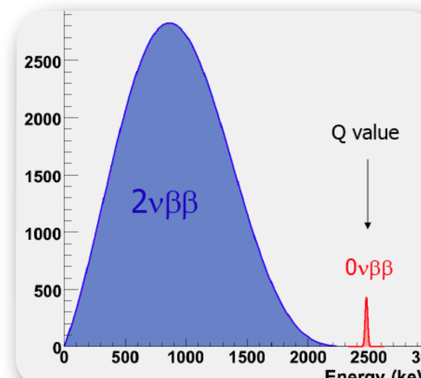
$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Isotope



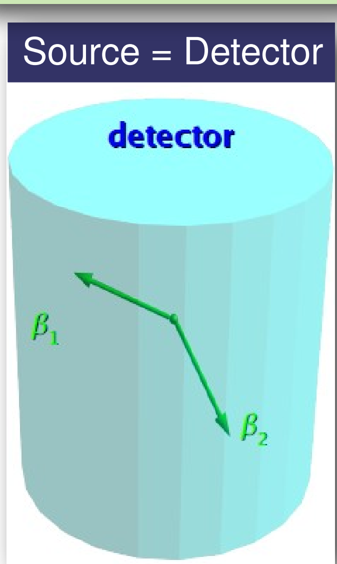
Find an isotope with large Q, no long lived radioactive isotopes, easy to procure and cheap.

ΔE



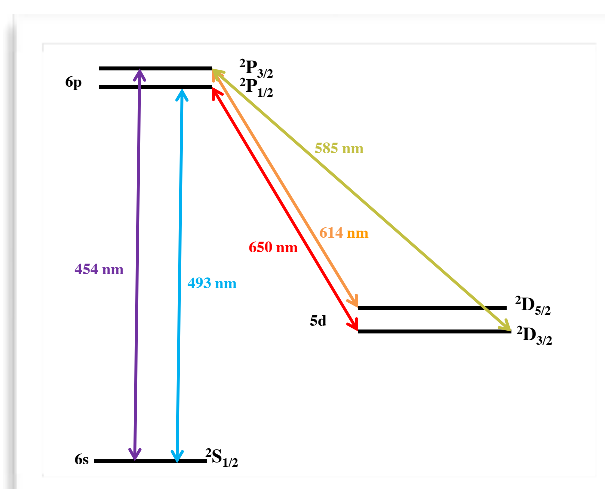
Build a detector with the best possible resolution

Scalability



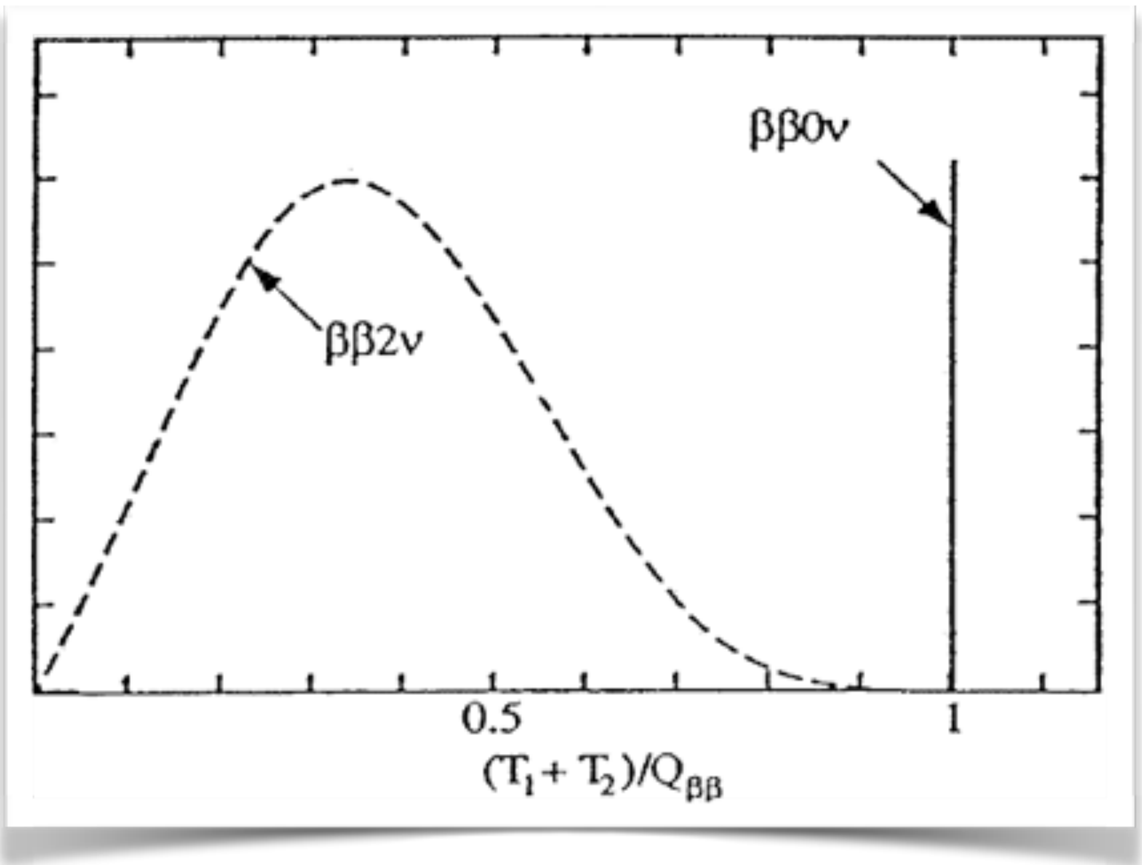
Build a detector with no dead areas, and economy of scale

Background



Detector provides extra handles to reduce background

Measuring ββ0ν in an ideal experiment



Measuring nothing is very difficult

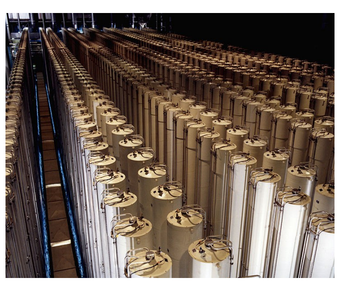
- Get yourself a detector with perfect energy resolution
- Measure the energy of the emitted electrons and select those with (T1+T2)/Q = 1
- Count the number of events and calculate the corresponding half-life.
- In Xe-136, a perfect detector of 1ton observes 3 events for a lifetime of 10^{27} y (~20 meV).
- Improvement with $\sqrt{T}$ but if you must subtract background then $\sqrt[4]{T}$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

Why NEXT? — Advantages of HPXe technology

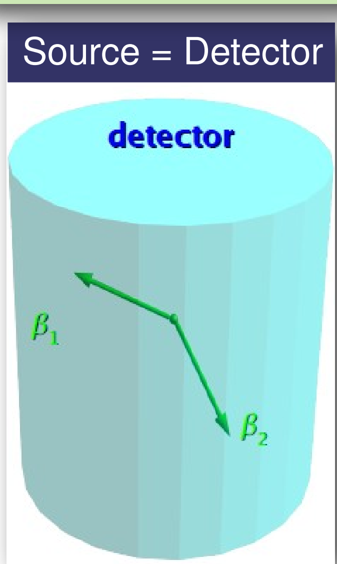
$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Cost



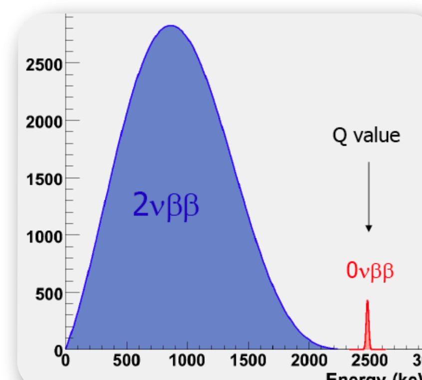
Xenon is the cheapest and easiest to enrich of all ββ isotopes. No long lived radioactive isotopes. There is already 1 ton of enriched xenon in the World.

Scalability



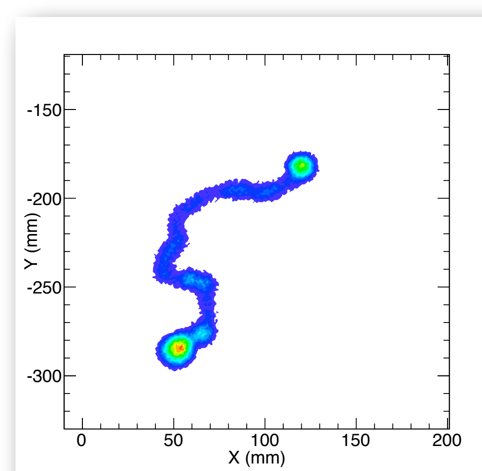
Xenon is a noble gas suitable to build a TPC. No dead areas, S/N improves with L

ΔE



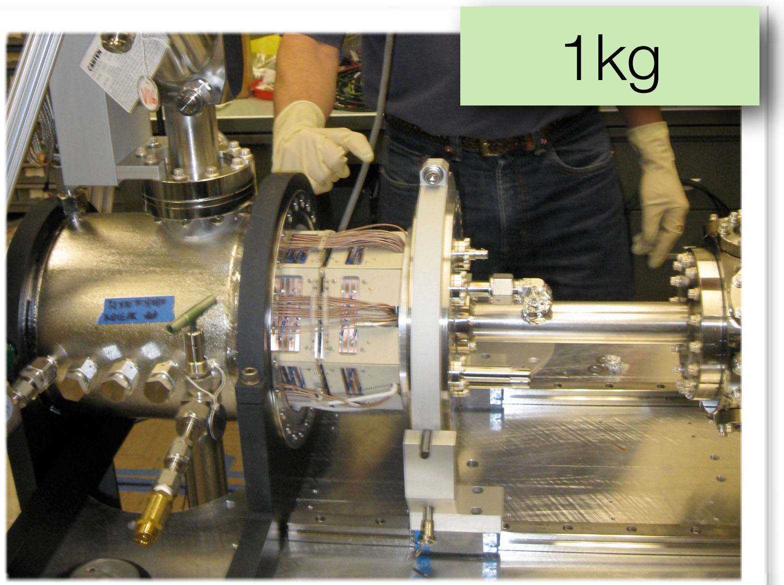
HPXe TPC is the only xenon detector that provides good energy resolution (better 1% FWHM at Qbb)

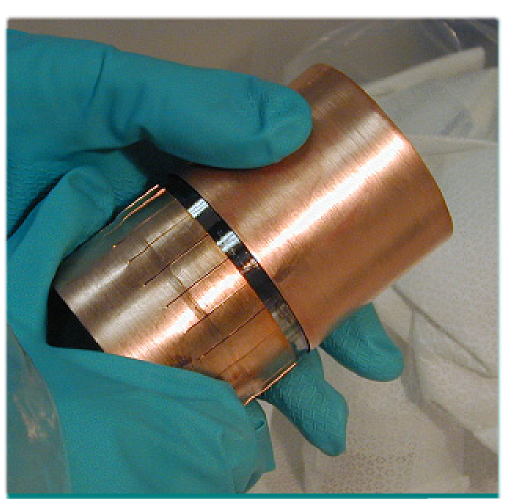
Background

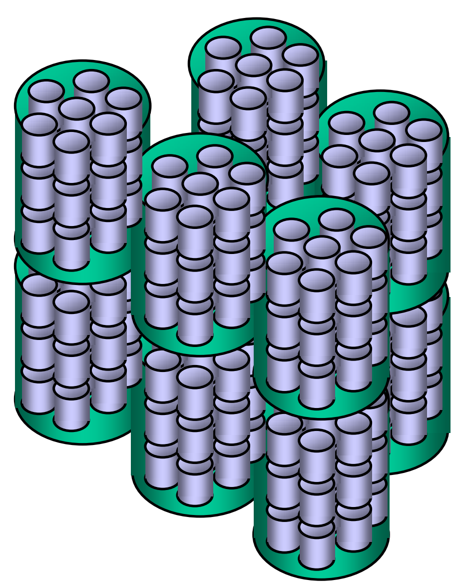


HPXe TPC is the only xenon detector that provides topological signal

Scalability





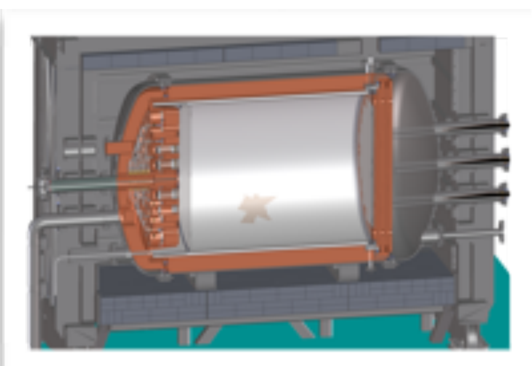


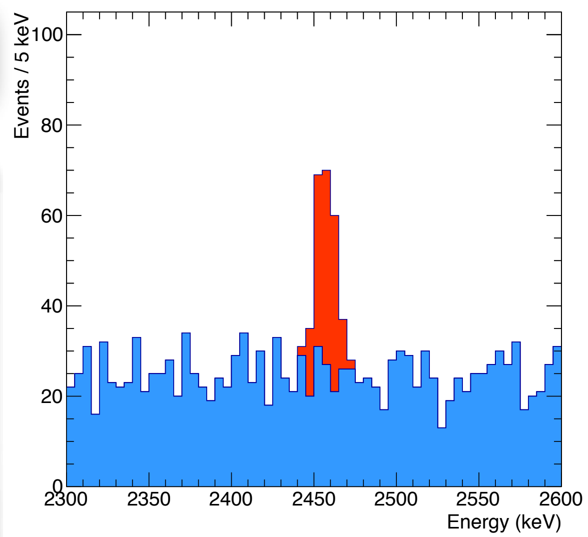
210 2.35 kg crystals

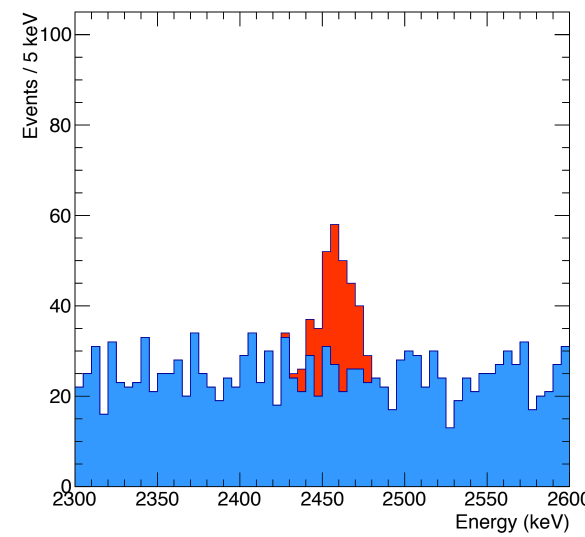
Economy of scale: Double L, signal increases 8 (L^3), background increases 4 (L^2), S/N improves by a factor 2

Energy resolution makes a difference

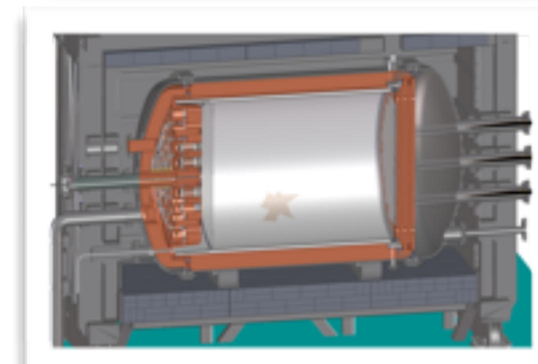
0,5 % FWHM



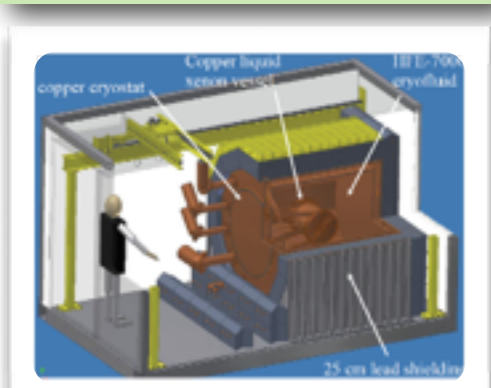


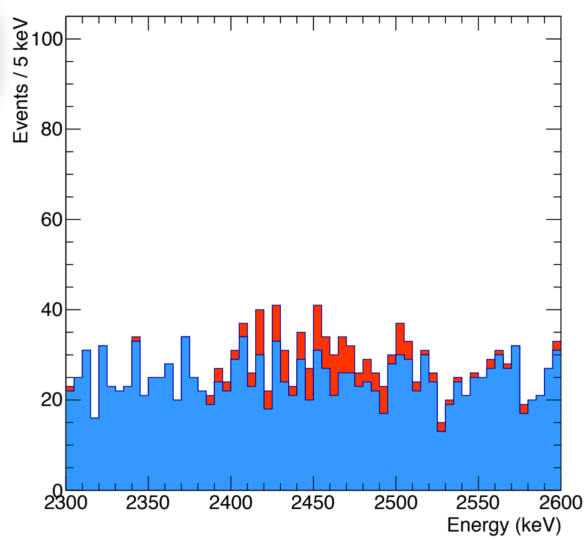


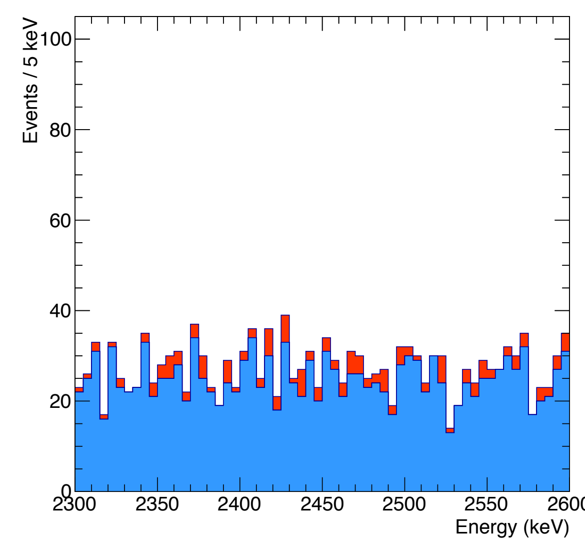
1,0 % FWHM



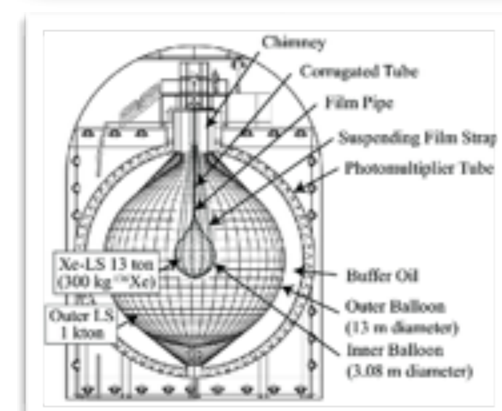
4,0 % FWHM







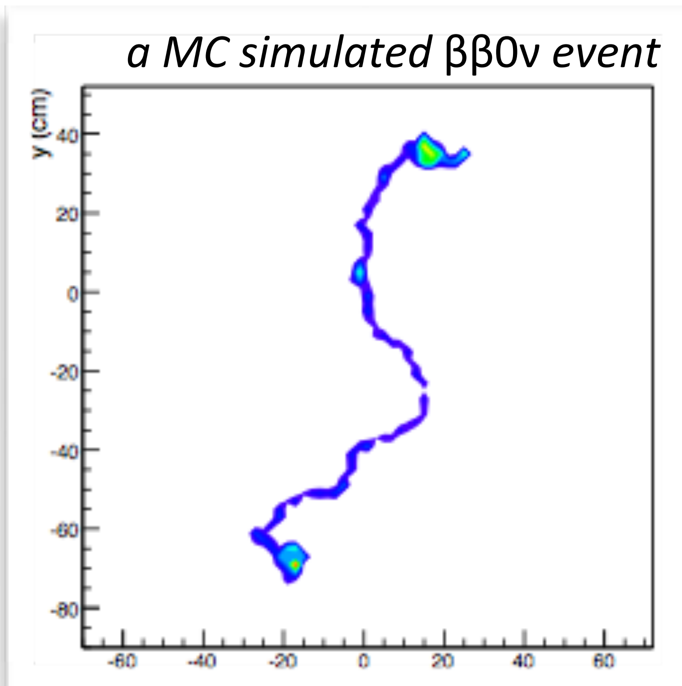
10 % FWHM

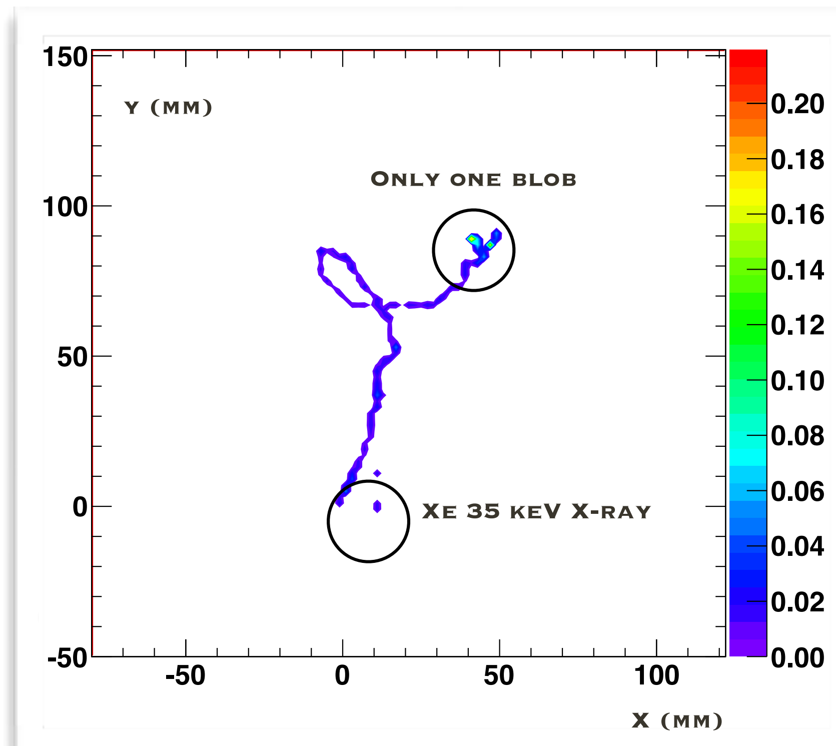


Signal and background:

- Signal: mν ~200 meV and an exposure of 5 ton year.
- Background 1 count/keV/ton/year.

Topological background reduction





- In xenon gas at 15 bar, a ββ event is a twisted track, 10 cm long, with two energy blobs at the two ends and no additional floating clusters.
- Instead the backgrounds are single electrons, accompanied 85% of the time by X-rays (Xenon de-excitation).
- HPXe TPC offers a signal that looks like a signal: two identified electrons with an energy within 10 keV of Qbb

HPXe and NEXT: a bit of history

J. Phys. G: Nucl. Part. Phys. 17 (1991) S231–S241. Printed in the UK

The Milano Experiment on Double Beta Decay of ^{136}Xe

E. Bellotti(*), O. Cremonesi, E. Fiorini, G. Gervasio, S. Ragazzi, L. Rossi(**), J. Szarka(***), P. P. Sverzellati, T. Tabarelli, L. Zanotti

Dipartimento di Fisica dell' Università di Milano & I.N.F.N. sezione di Milano
(*) also I.N.F.N. Laboratori Nazionali del Gran Sasso (L.N.G.S.)
(**) I.N.F.N. sezione di Genova
(***) also Comenius University - Bratislava

ABSTRACT : An experiment on double β decay of ^{136}Xe has been performed at the Gran Sasso Underground Laboratory (L.N.G.S.). The detector was a multicell proportional counter, built from selected low background materials, which was filled alternatively with natural Xenon, enriched Xenon to 64% in the ^{136}Xe isotope, and natural Xenon cleaned by ultracentrifugation, and heavily shielded against environmental radioactivity. After 6000 hours of operation half lifetime for the neutrinoless decay mode turns out to be greater than 2×10^{22} y at 90% C.L. A limit of 6×10^{19} y, also at 90% C.L., is reported for the 2ν decay mode.

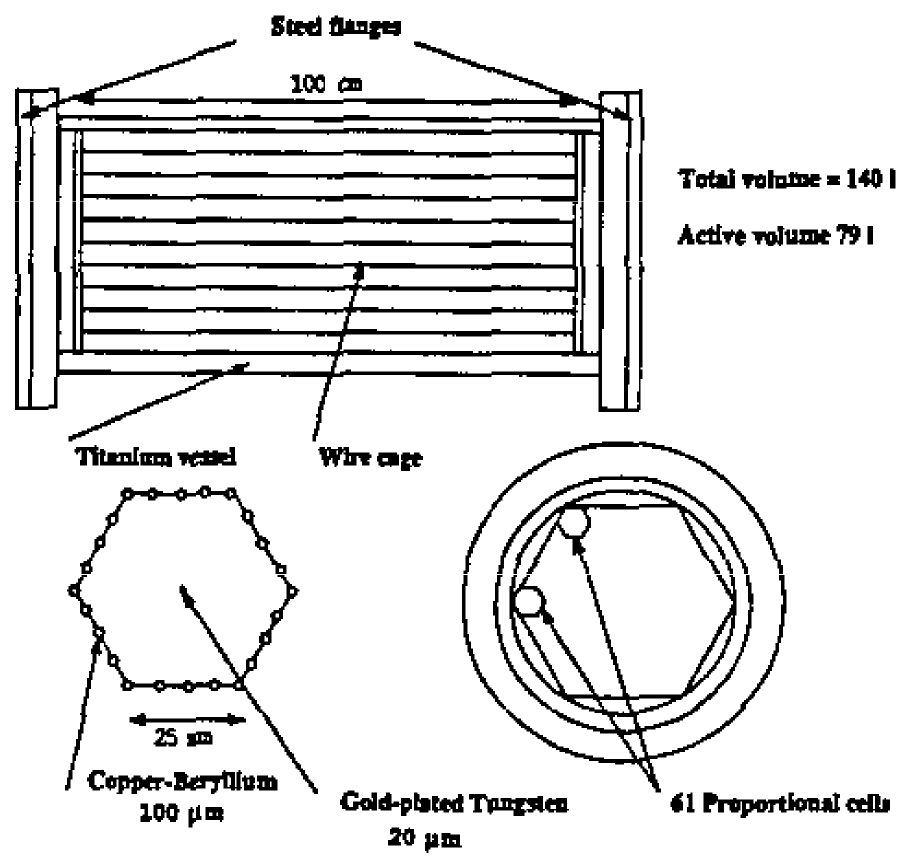
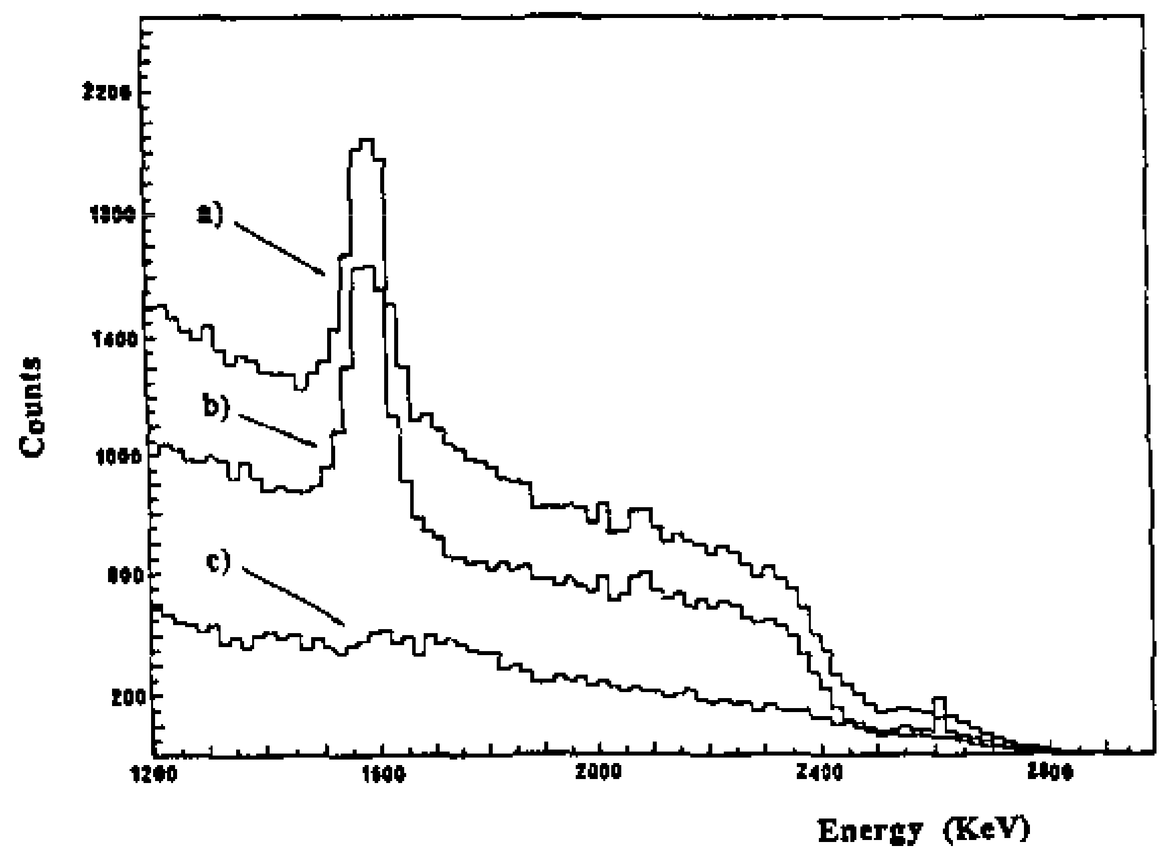


Fig. 1. Detector layout and single cell scheme.

The detector is a multicell proportional counter consisting of 61 contiguous cells (fig. 1). Each cell is hexagonal and has a central anode wire of gold plated tungsten (~ 20 μm diameter) surrounded by 24 cathode wires (copper-beryllium, 100 μm diameter); all cells are arranged in a honeycomb structure. Overall detector volume is 140 l, with a cell dimension of 2.5 cm ø x 80 cm length and active volume is 79 l. The wire cage is enclosed in a Ti vessel with steel flanges. The detector has been operated at the pressure of 9.5 bar with three different gas fillings:

single wire	~ 7.5%	@	122 keV
all wires	~ 8.0%	@	661 keV
	~ 5.0%	@	1592 keV

the latter point being obtained using the double escape peak of the 2615 keV γ line of ^{208}Tl.



About 4 % **FWHM at Qbb**

J. Phys. G: Nucl. Part. Phys. 17 (1991) S165–S172. Printed in the UK

First 0ν Half-life Limit from the Gotthard Xenon Time Projection Chamber

H.T. Wong [α] F. Boehm [α], P. Fisher [α], K. Gabathuler [β], H.E. Henrikson [α], D.A. Imel [α], M.Z. Iqbal [α], V. Jörgens [γ], L.W. Mitchell [γ], B.M. O'Callaghan-Hay [α], J. Thomas [α], M. Treichel [γ], J.-C. Vuilleumier [γ], J.-L. Vuilleumier [γ].

[α] Norman Bridge Laboratory of Physics, California Institute of Technology, Pasadena, California 91125, U.S.A.

[β] Paul Scherrer Institute (formerly SIN), 5234 Villigen, Switzerland.

[γ] Institut de Physique, A.-L. Breguet 1, 2000 Neuchâtel, Switzerland.

ABSTRACT: A xenon Time Projection Chamber with an active volume of 207 liters has been built to study 0ν and 2ν double beta decay in ^{136}Xe. The TPC has been installed in the Gotthard Tunnel Underground Laboratory, and is currently taking data with 5 atm of xenon enriched in 62.5% ^{136}Xe. The first 166 hours of data are presented. Based on this data set, we deduce a half-life limit of $T^{0\nu}_{\frac{1}{2}}(0^+ \rightarrow 0^+) > 6.2 \times 10^{21}$ years for the 0ν mode, at a 90% C.L.

Gothard TPC

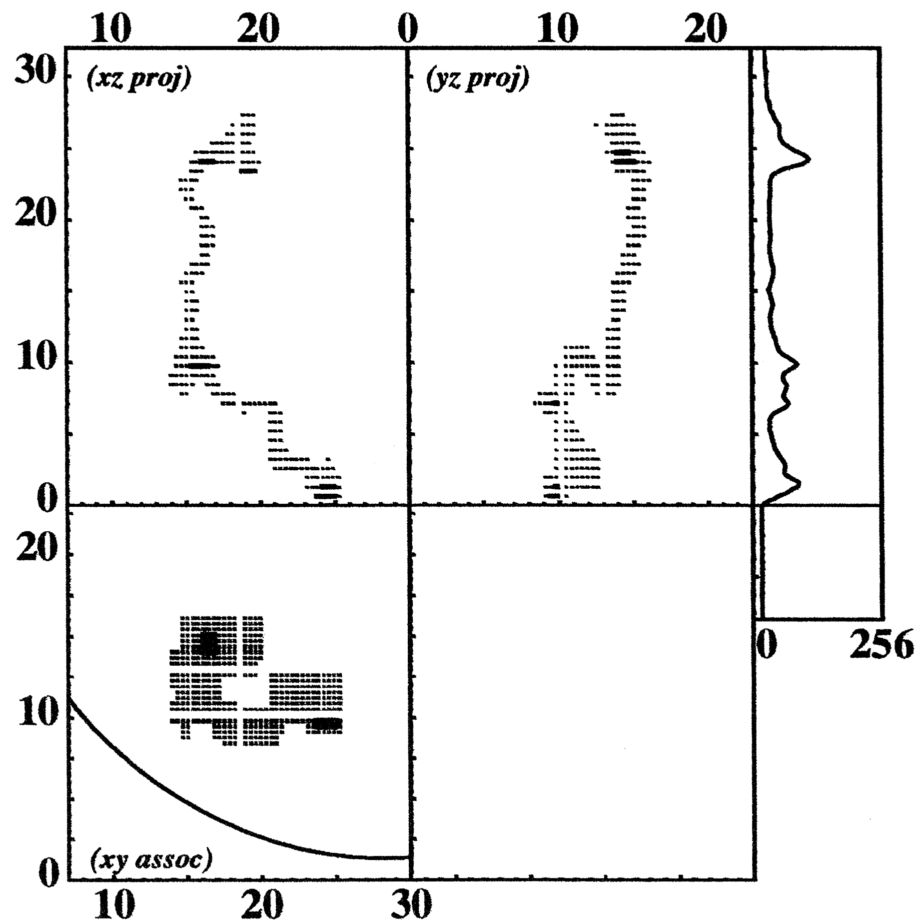


Fig. 2. A typical 'two electron' candidate: the xz and yz projection, as well as the extracted $x-y$ projections (in the lower frame) are drawn. Scales are in cm. The time evolution of the anode signal is displayed on the right. The $\beta\beta$-candidate exhibits 'blobs' at *both* ends of a continuous track.

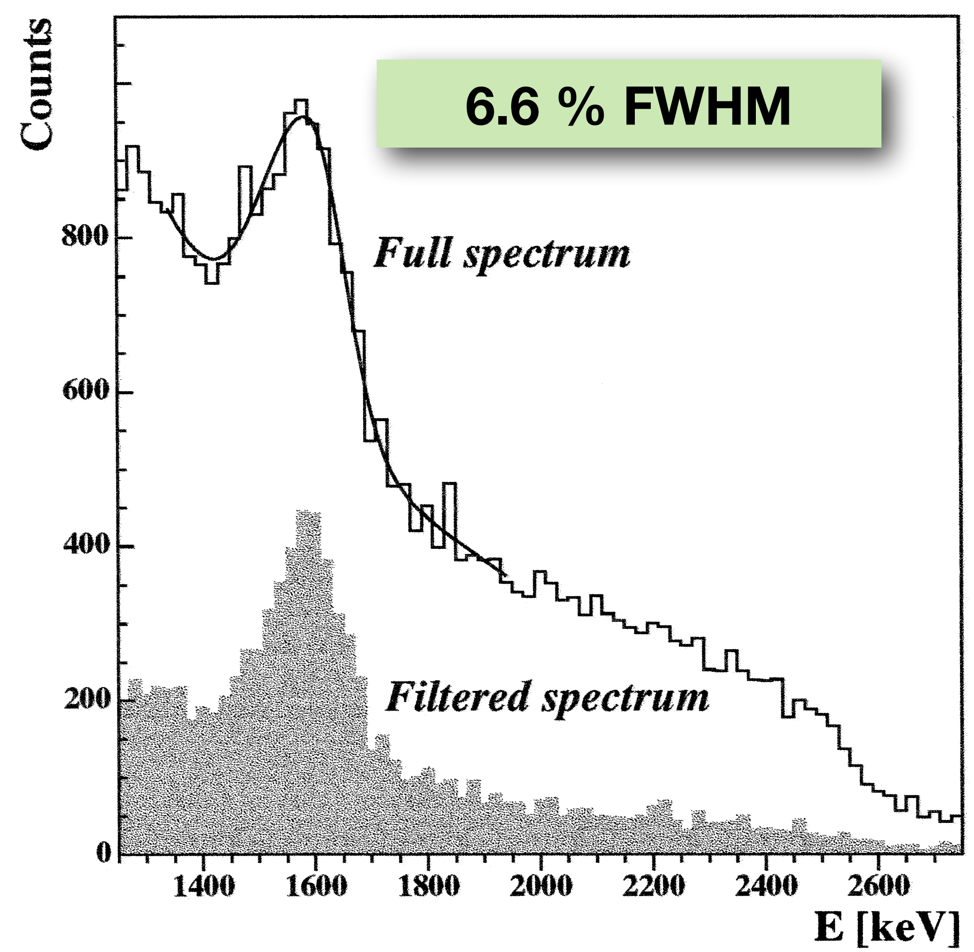
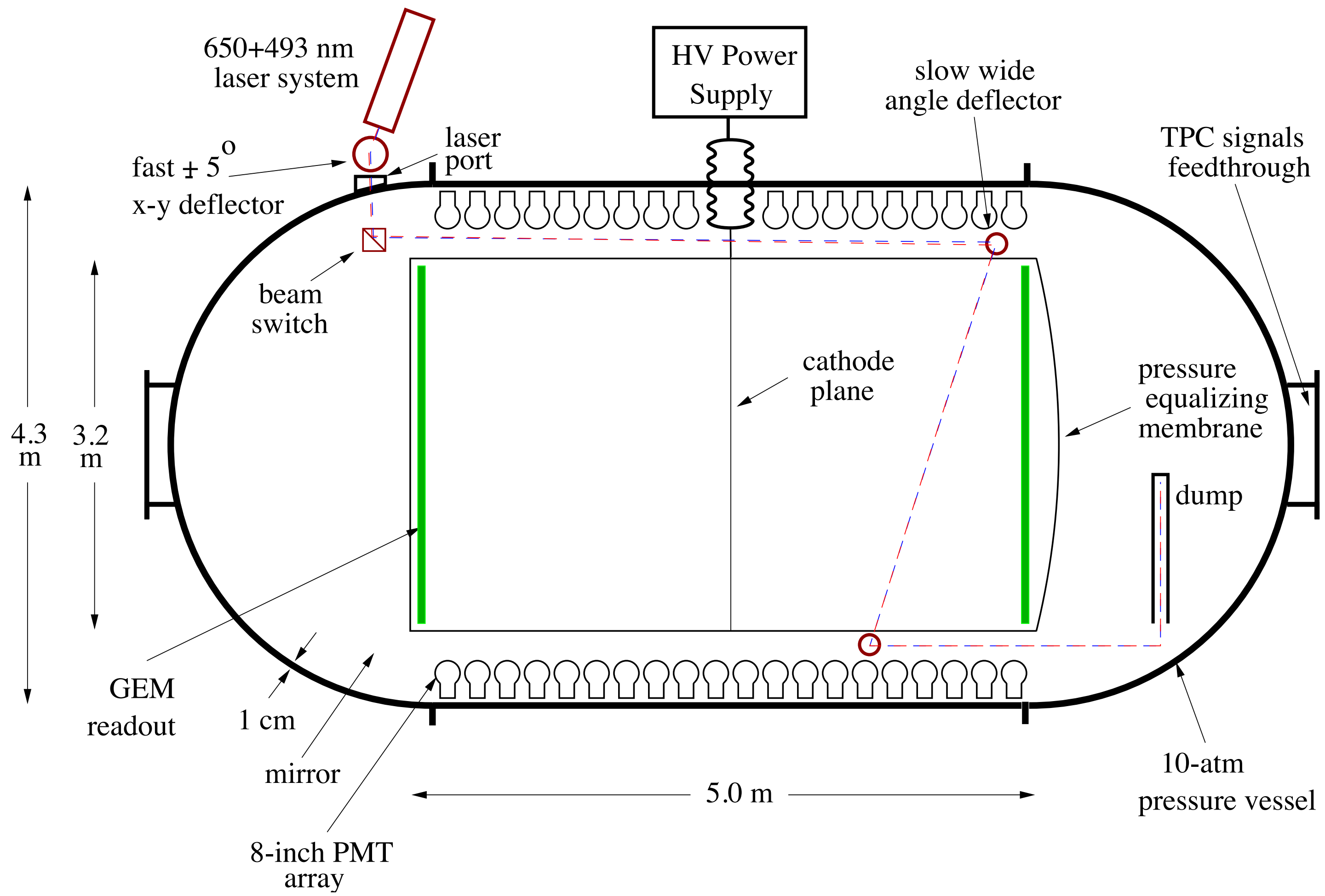


Fig. 4. Energy spectrum of a ^{232}Th source. The peak is due to the double-escape of the 2614-keV γ-rays in ^{208}Tl. The full spectrum is shown, as well as the spectrum obtained after filtering the events with our track-reconstruction program (selecting 'two-electron' events).

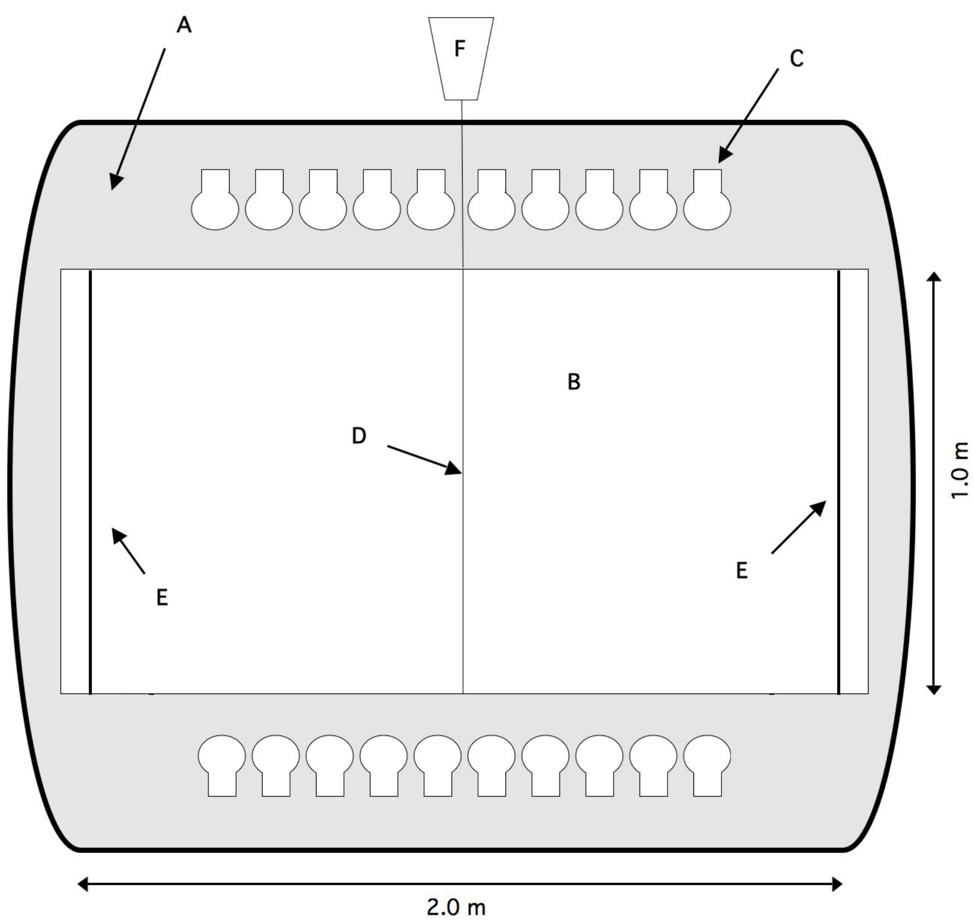
- Classical "gain" TPC: wires + pads: quencher CH4 (4%).
- Observed topological signature (spaghetti with two meat balls)
- Quencher killed the scintillation light: no t0, poor energy resolution.
- "Final" results of Gothard in 1998.

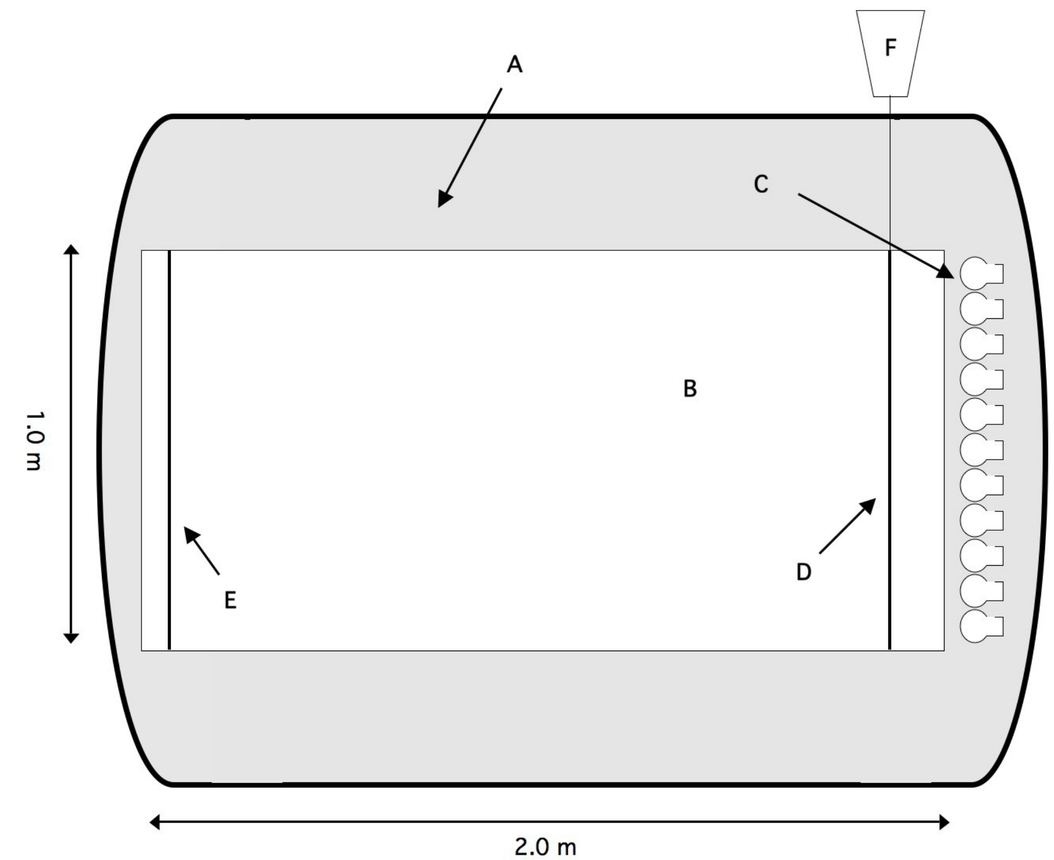
EXO white paper (1999)



- Symmetric TPC at 5 bar. Total volume of 40 m3 for 1 ton mass.
- "double vessel" with buffer gas
- Included the notion of "Ba Tagging"
- Included the notion that scintillation light had to be observed for t0.
- 1Kv/cm… huge electric field in the cathode.
- GEM readout. Estimated energy resolution was ~3% FWHM Qbb

NEXT EOI (2008)





“The readout will probably be done with micro pattern device (Micromegas, LEM and GEM are suitable alternatives) although the use of wires is not excluded”

- Ten years later: The NEXT EOI was essentially a modest version of EXO
- Still thinking in “gain” TPCs with micro pattern readout.

The breakthrough

2009: D. Nygren **High-pressure xenon gas electroluminescent TPC for 0-n bb-decay**

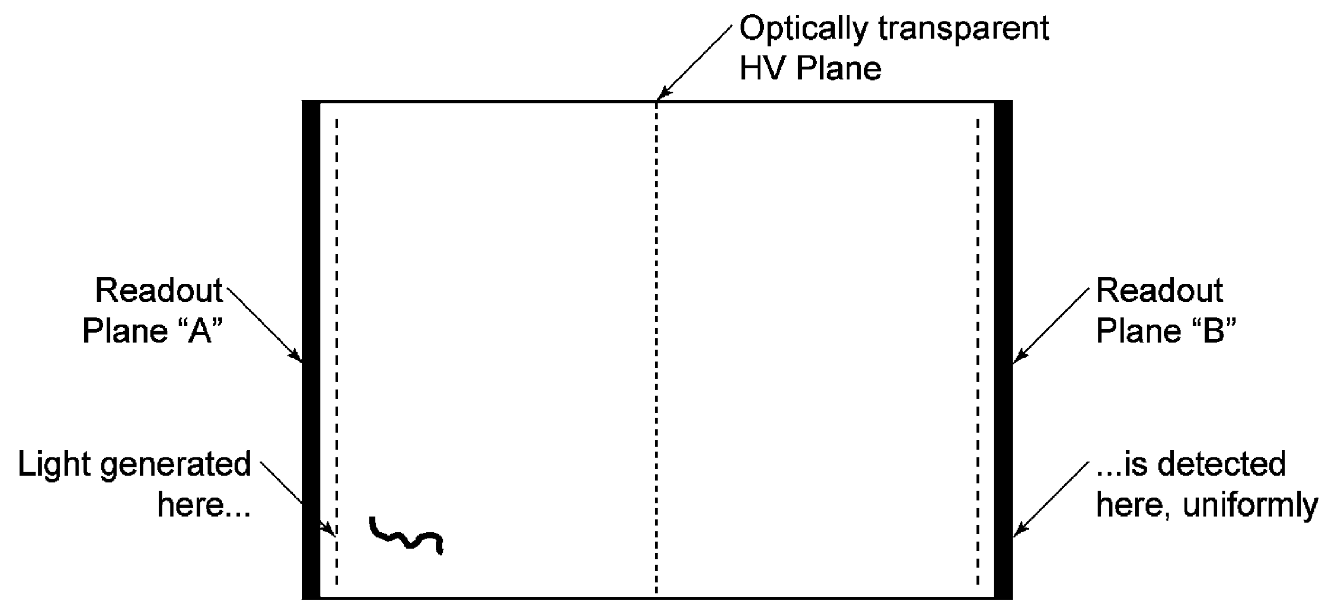
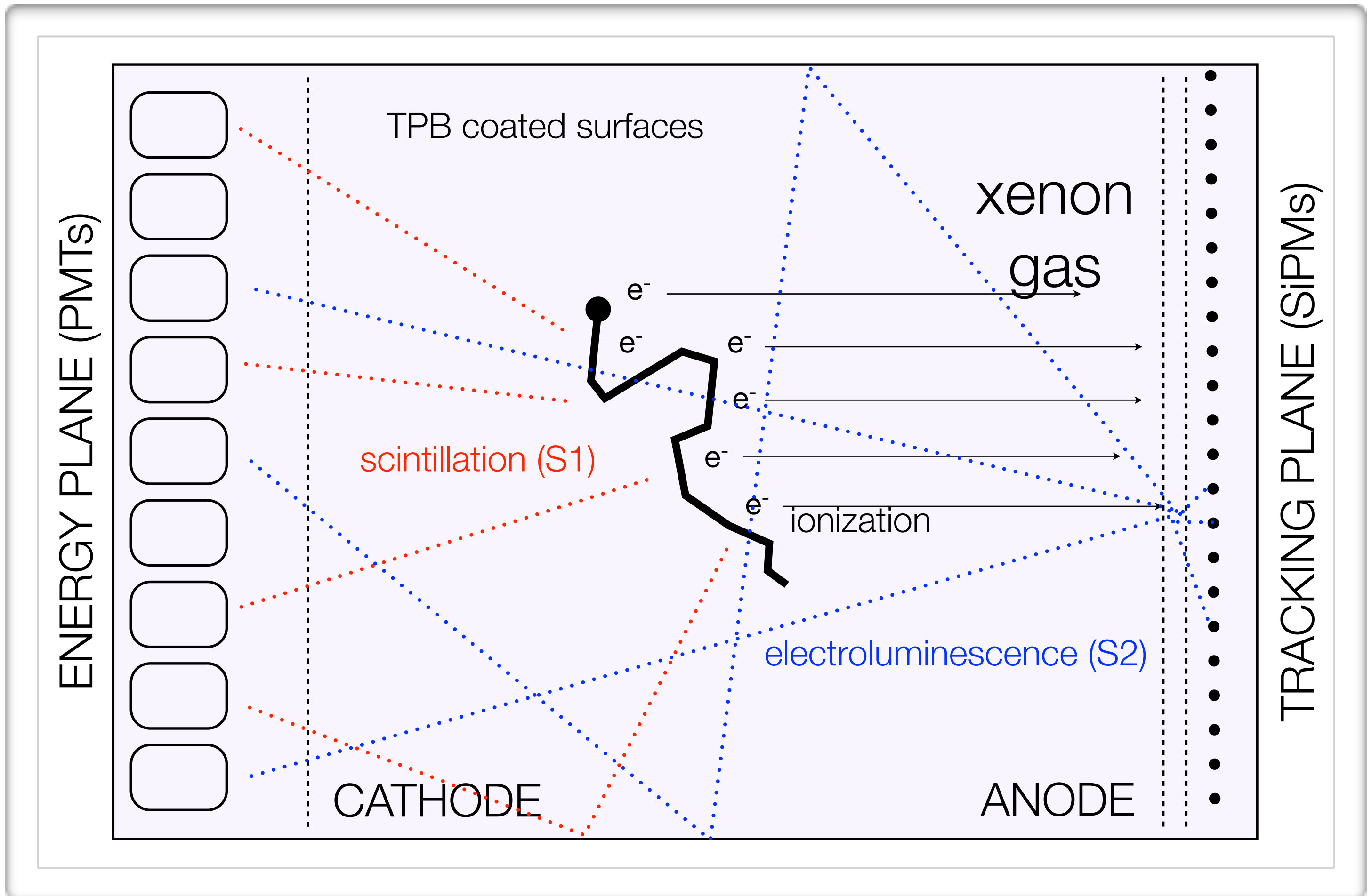


Fig. 3. Separated-function concept, illustrating the possibility to detect EL light at plane B originating from plane A, or vice-a-versa. The event, shown as a wiggly track, generates primary scintillation recorded at both planes. Subsequently, EL light generated at plane A is detected almost uniformly everywhere on plane B for a precise energy measurement.

"A high-pressure xenon gas TPC can provide both event topology information and optimized energy resolution for the detection of bb decay in ^{136}Xe. The result of optimization indicates that, at the ^{136}Xe Q-value of 2480 keV, an energy resolution of dE/E < 5x 10-3 FWHM may be realizable, even at the 1000 kg scale. Signal detection by electroluminescence appears essential to realize this performance."

Nuclear Instruments and Methods in Physics Research A 603 (2009) 337–348

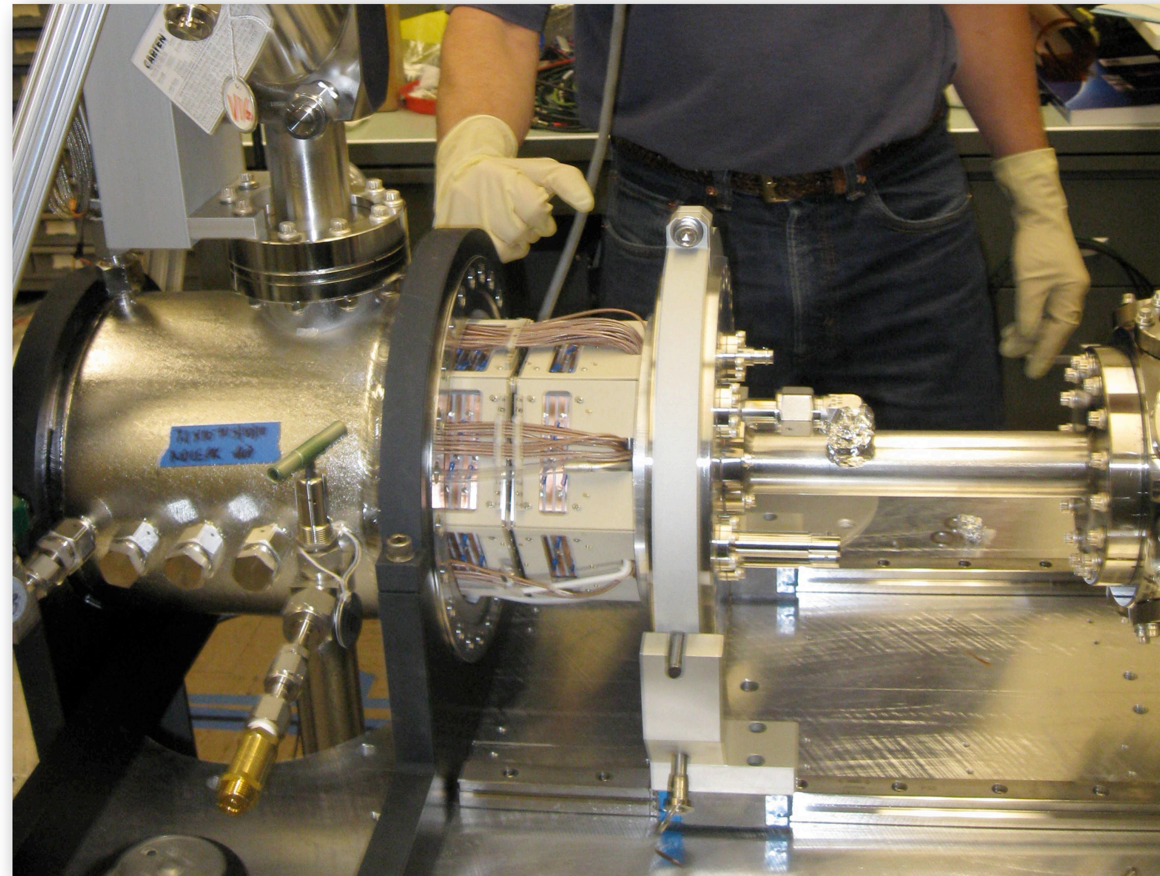
NEXT: A light TPC



EL mode is essential to get lineal gain, therefore avoiding avalanche fluctuations and fully exploiting the excellent Fano factor in gas

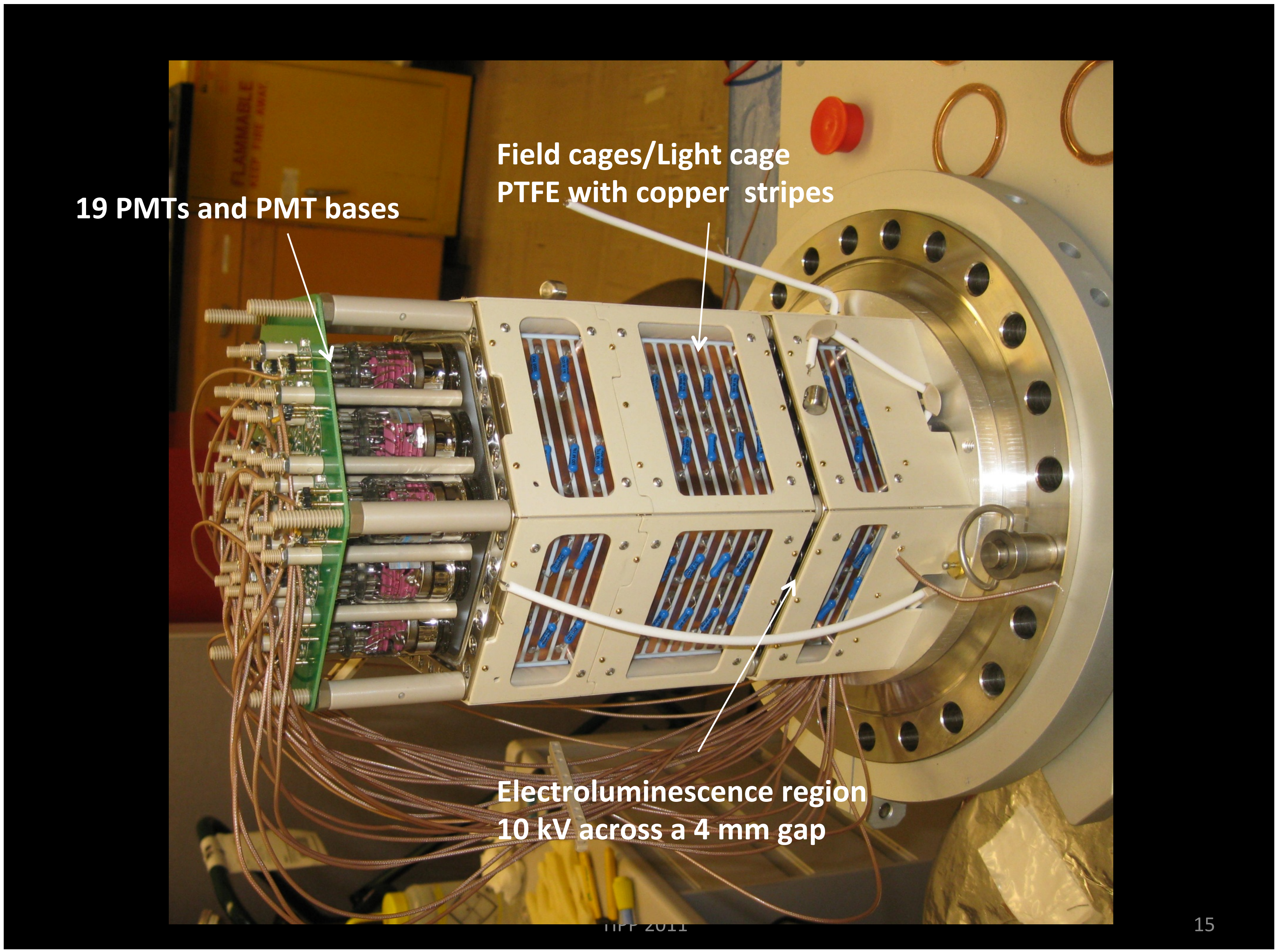
- It is a High Pressure Xenon (HPXe) TPC operating in EL mode.
- It is filled with 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane), which also provide t0.
- The event topology is reconstructed by a plane of radiopure silicon pixels (MPPCs) (tracking plane).

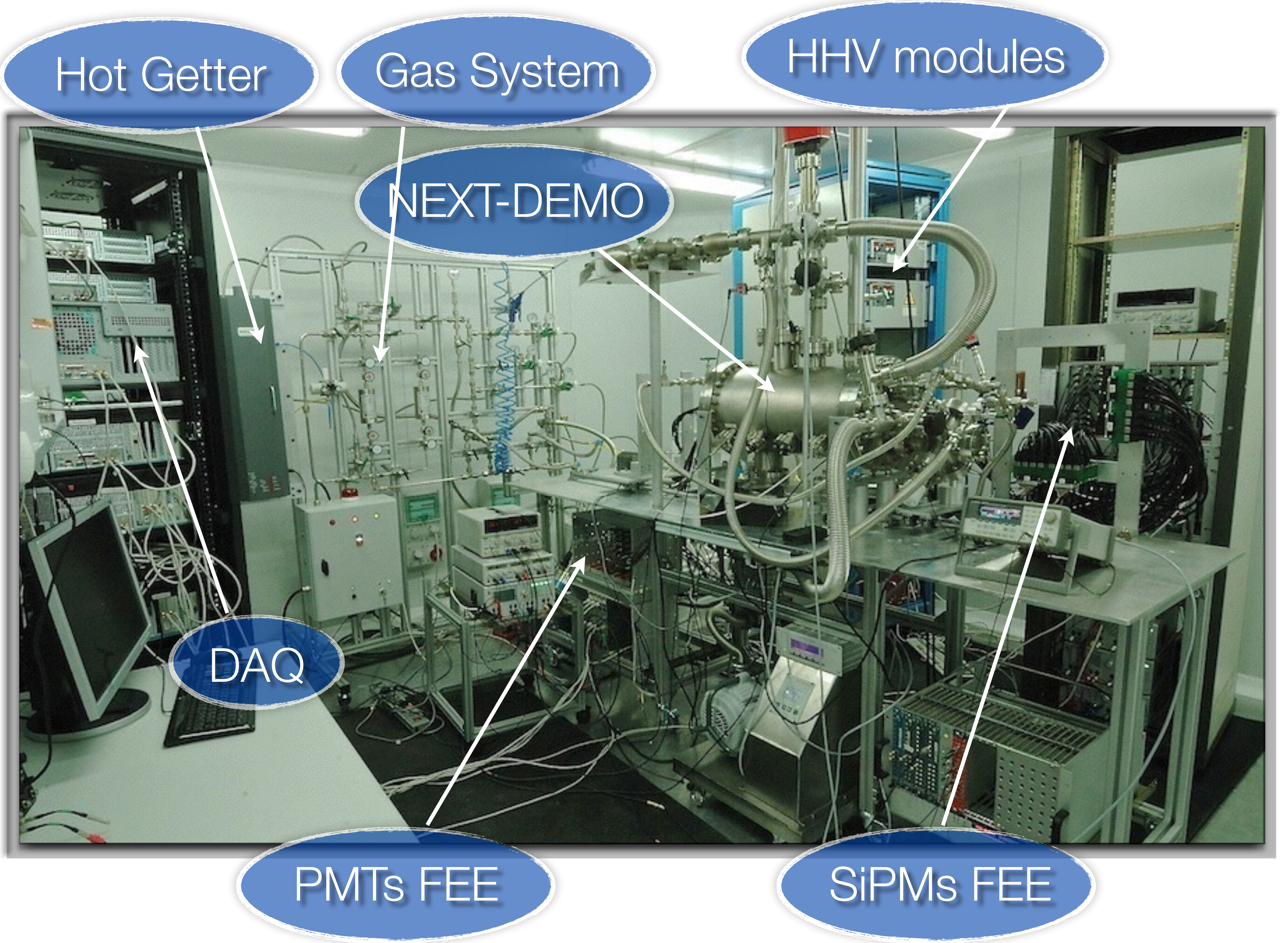
2010/2011: DEMO (IFIC) and DBDM EL prototypes (LBNL) built and commissioned



DEMO @ IFIC made possible thanks to the crucial contribution of J. White and Dave Nygren. Spanish groups benefited enormously from USA groups know-how.

DBDM: Best resolution to date

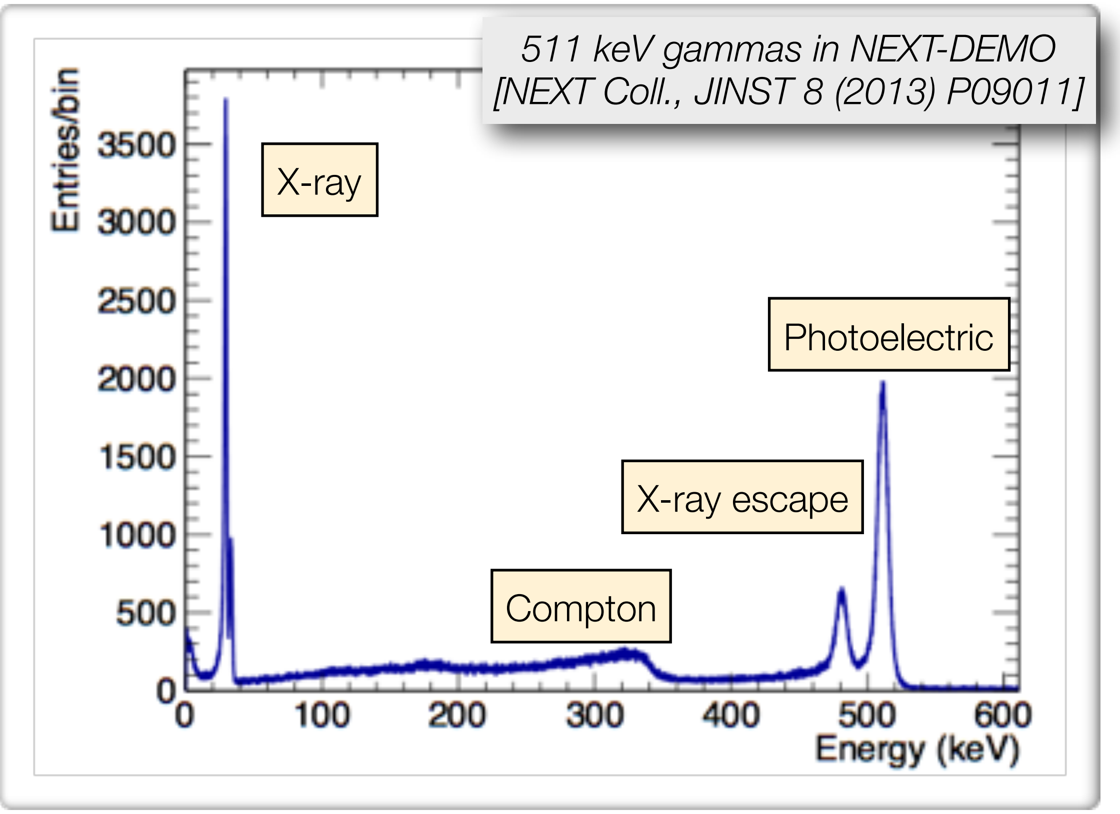



Hot Getter
Gas System
HHV modules
NEXT-DEMO
DAQ
PMTs FEE
SiPMs FEE

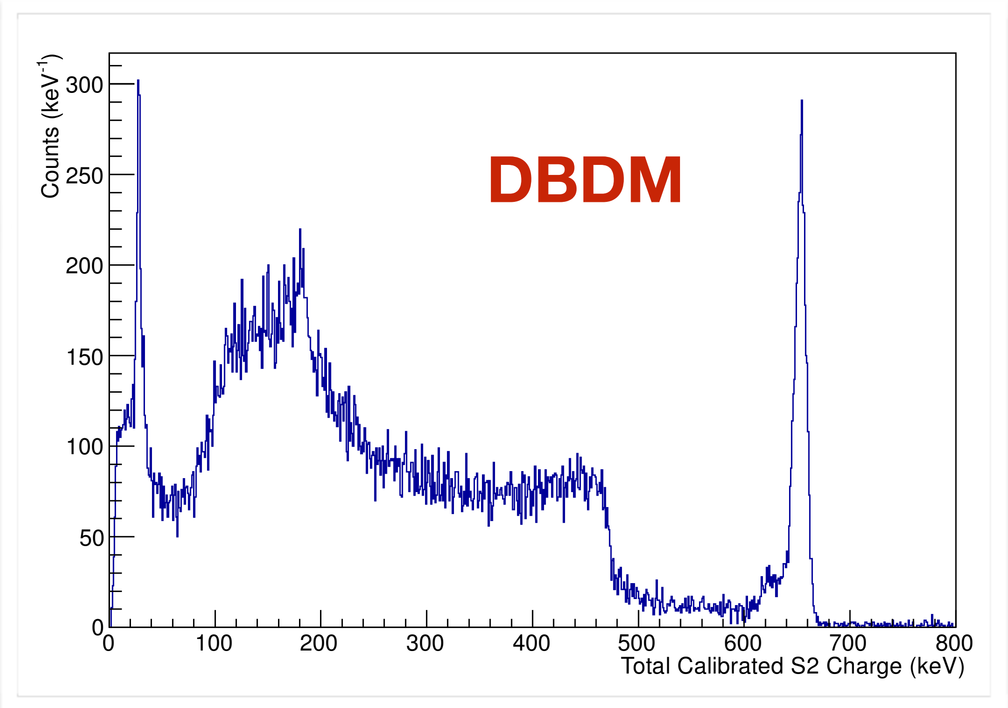
NEXT R&D: detector performance achievements

- 1.8% FWHM energy resolution for 511 keV electrons over large fiducial volume

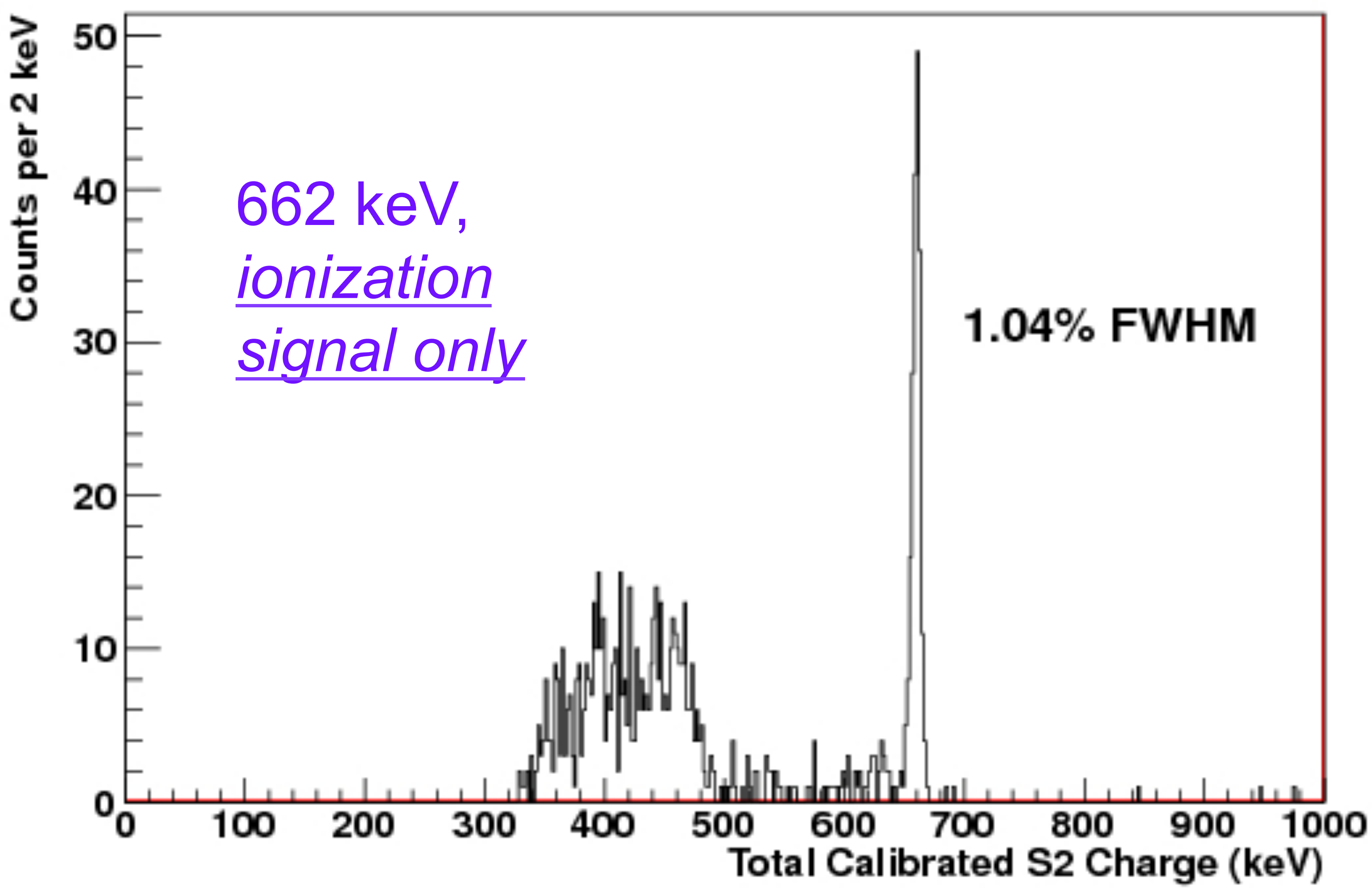
- Extrapolates to 0.75% FWHM at $Q_{\beta\beta}$ energy of 136Xe decay



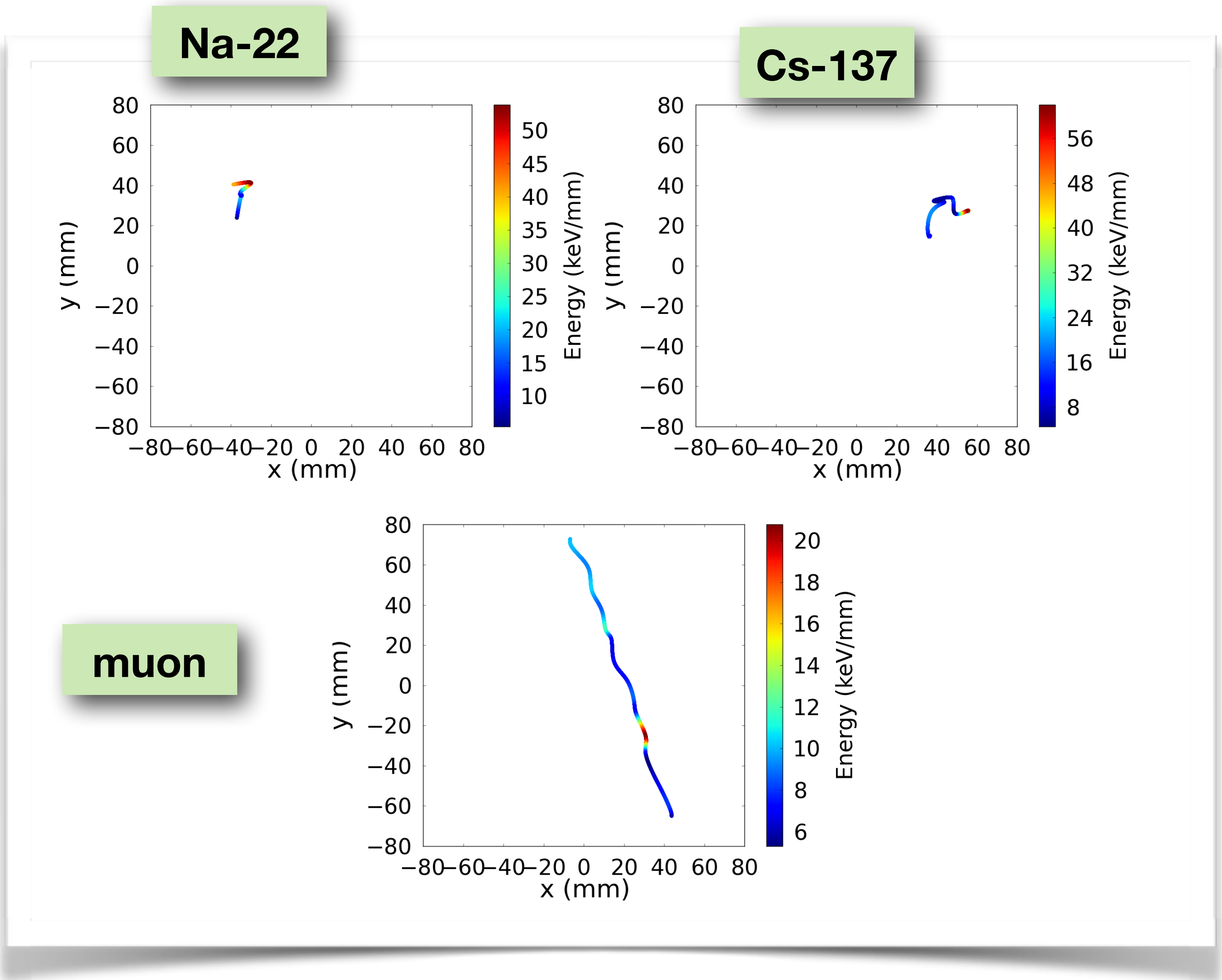
- The DBDM prototype at LBNL extrapolates to **0.5 % FWHM** at $\mathbf{Q_{\beta\beta}}$ using 660 Cs-137 electrons

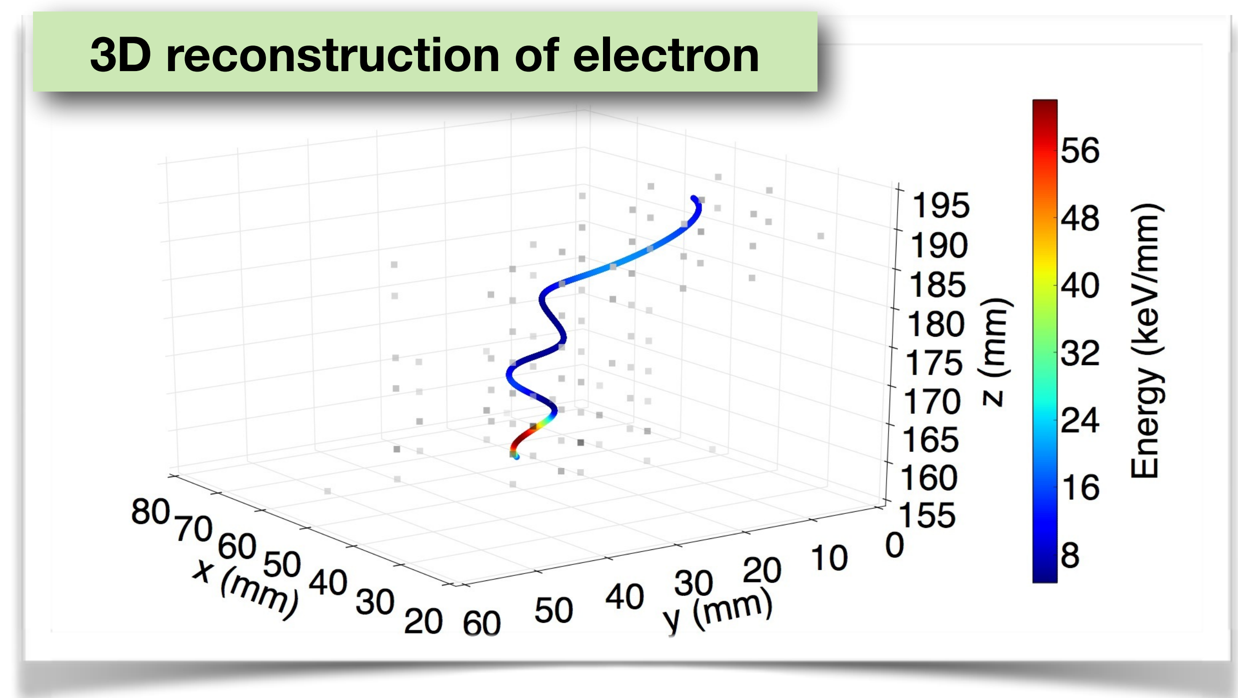


The beauty of resolution



Topology of the signal in next





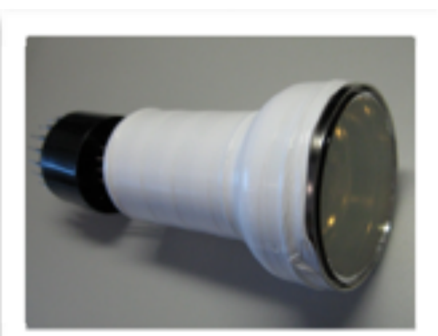
- Higher energy deposition clearly visible at electron track end-point.
- Tracks reconstructed using SiPMs + PMTs

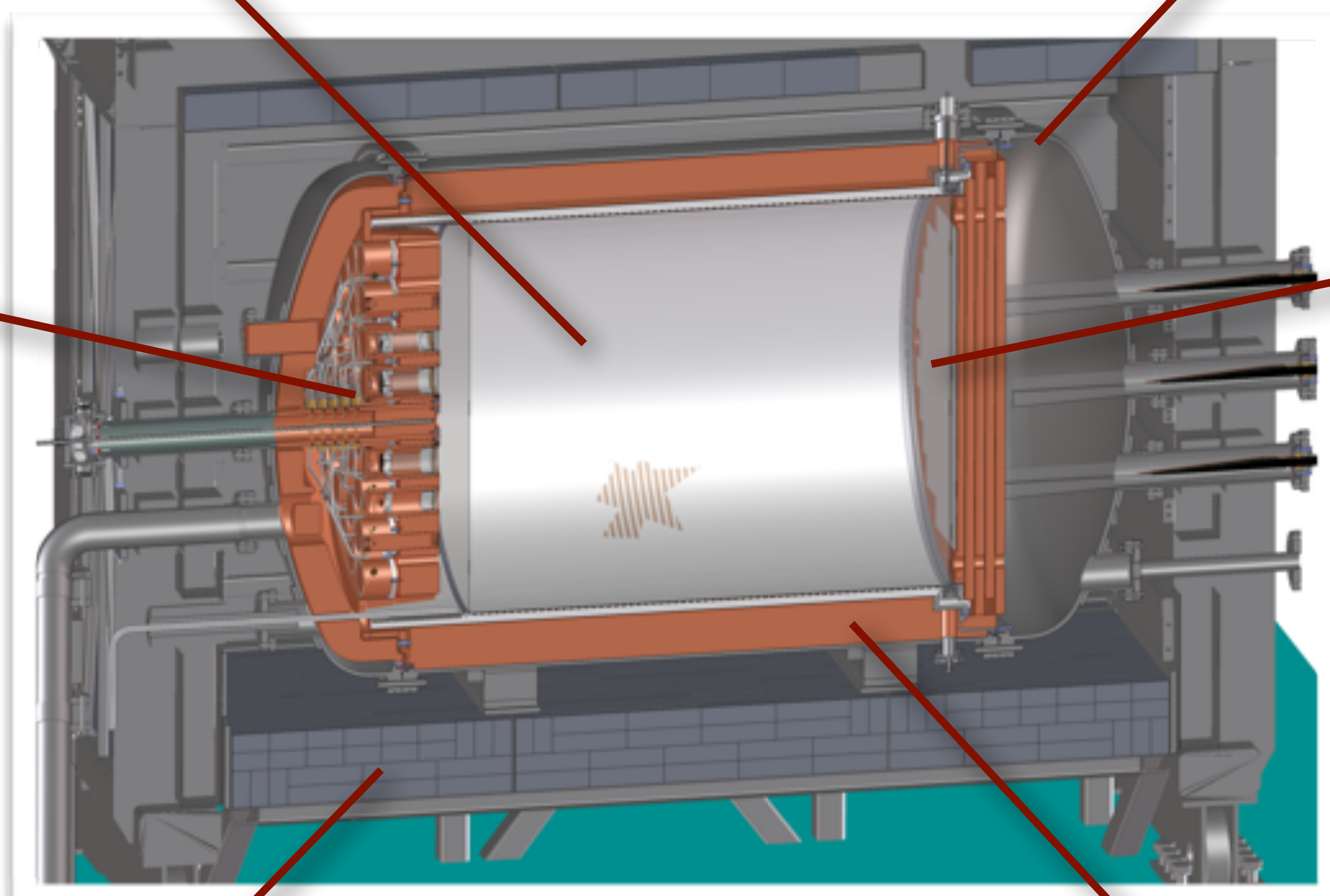
NEXT 100 kg detector at LSC: main features

Time Projection Chamber:
100 kg active region, 130 cm drift length

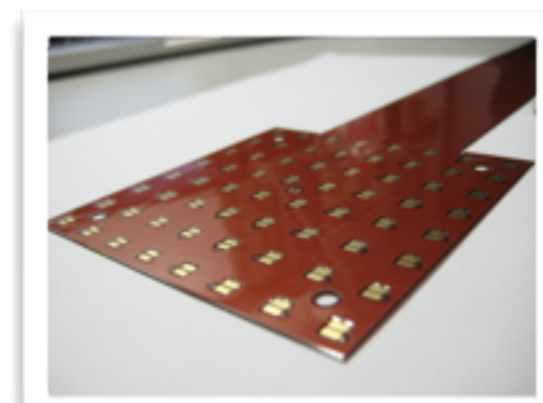
Pressure vessel:
stainless steel,15 bar max pressure

Energy plane:
60 PMTs,
30% coverage





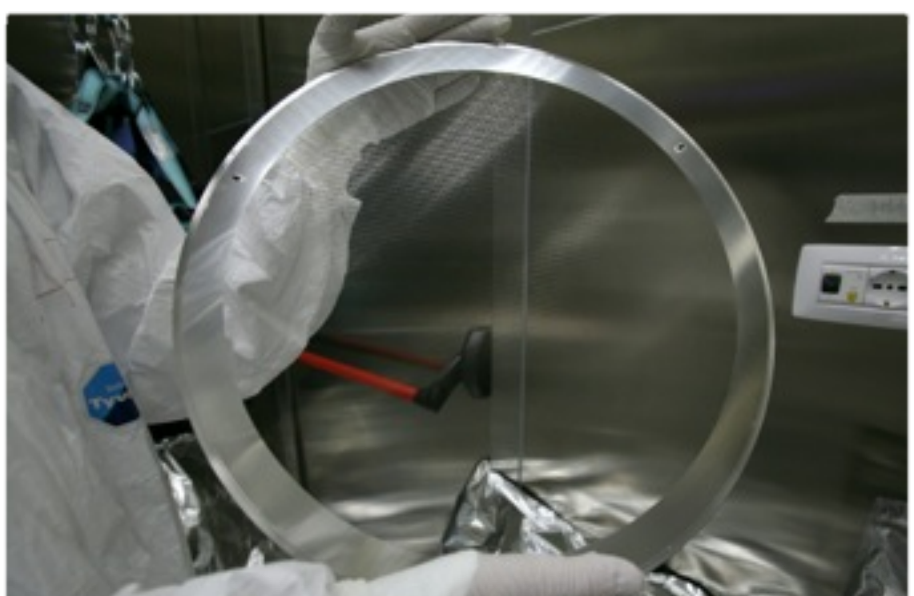
Tracking plane:
7,000 SiPMs,
1 cm pitch



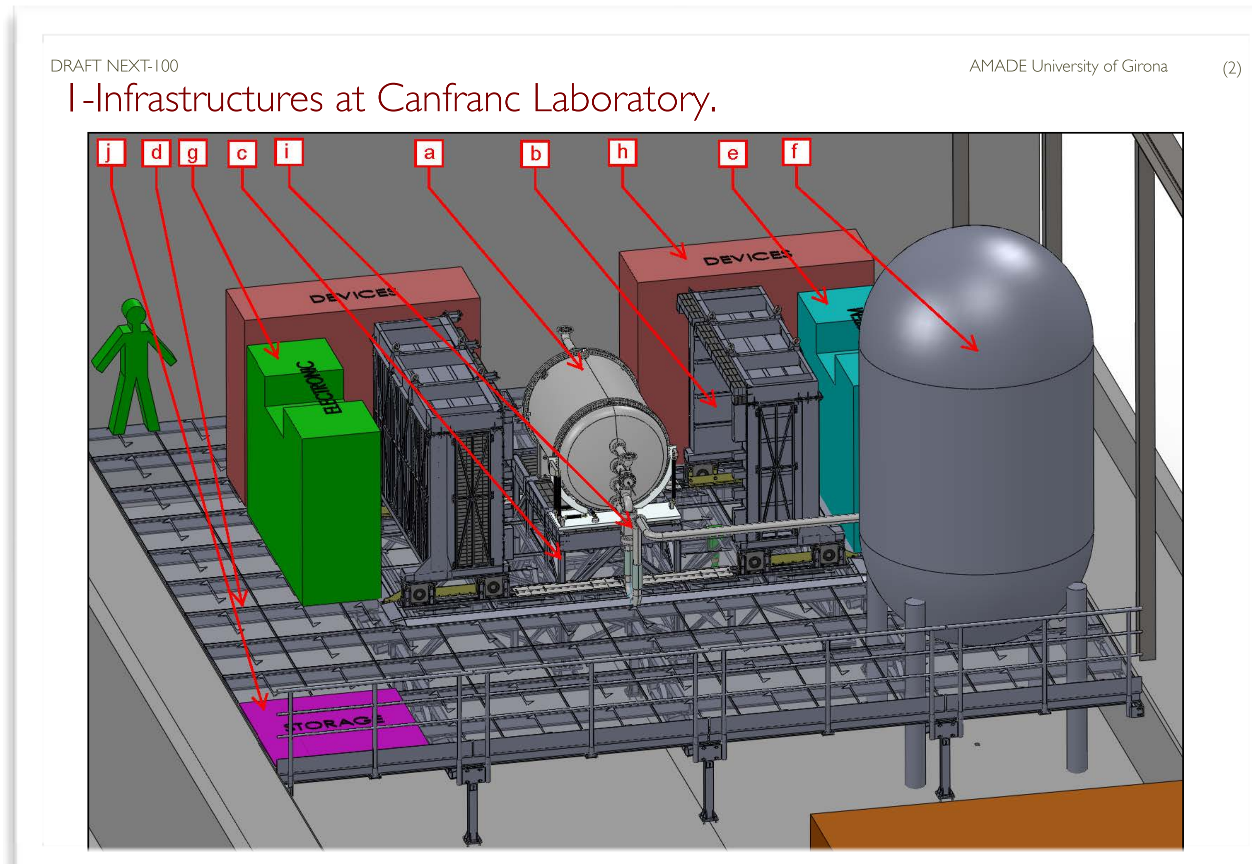
Outer shield:
lead, 20 cm thick

Inner shield:
copper, 12 cm thick

Pressure vessel

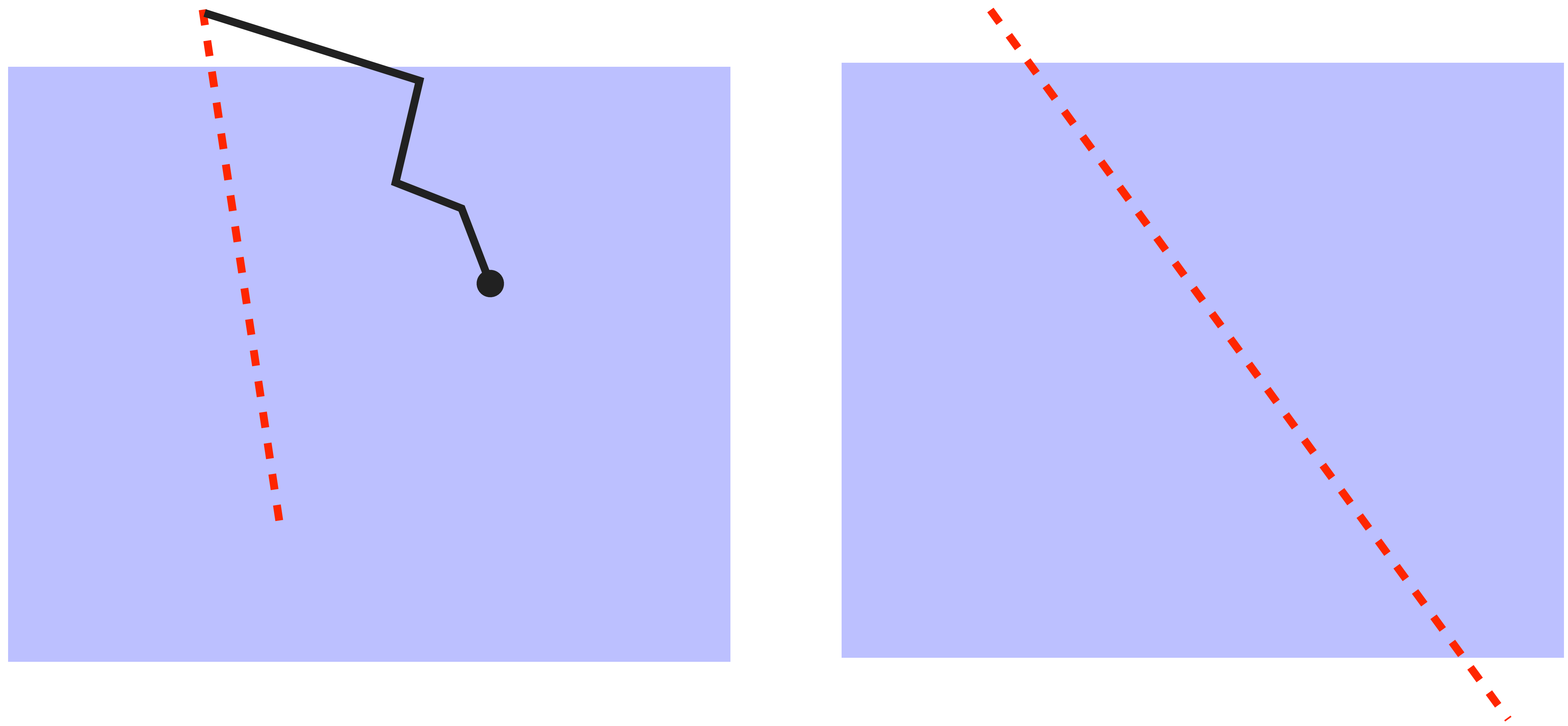


NEXT at LSC



Infrastructures: platform, lead castle, gas system, emergency recovery system, completed. First phase of experiment starts in 2015. In stock, 100 kg of enriched xenon and 100 kg of depleted xenon.

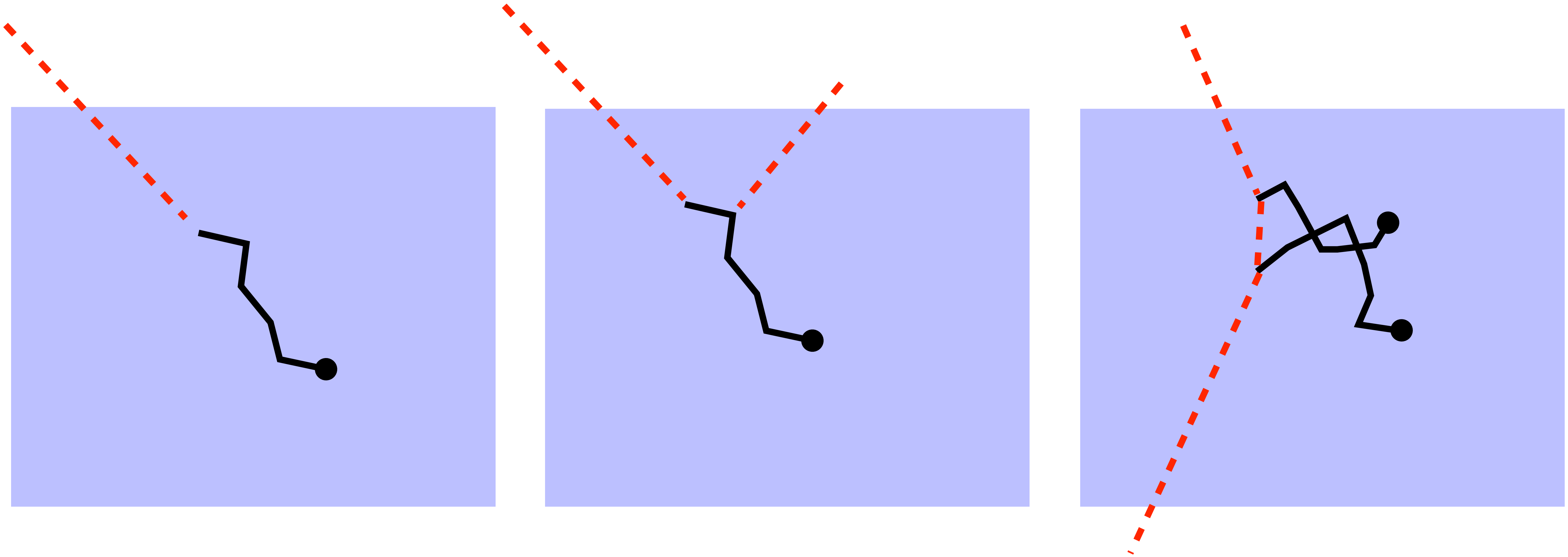
NEXT100 rejection of backgrounds



<u>A transparent target, away from surfaces</u>

- Veto of effectively all charged backgrounds entering the detector (left). High-energy gammas have a long interaction length (>3 m) in HPXe.

NEXT100 rejection of backgrounds



The 2-electron signature

- Interaction of high-energy gammas (from Tl-208 and Bi-214) in the HPXe can generate electron tracks with energies around the Q value of Xe-136. However, electron often accompanied of satellite clusters and single blob deposit

NEXT100 rejection of backgrounds

	$0\nu\beta\beta$	Tl-208	Bi-214
Fiducial E>2 MeV	67.86%	0.25%	0.01%
ROI	95.52%	8.99%	64.66%
1 track	74.60%	1.86%	12.54%
2 blobs	73.76%	9.60%	9.89%

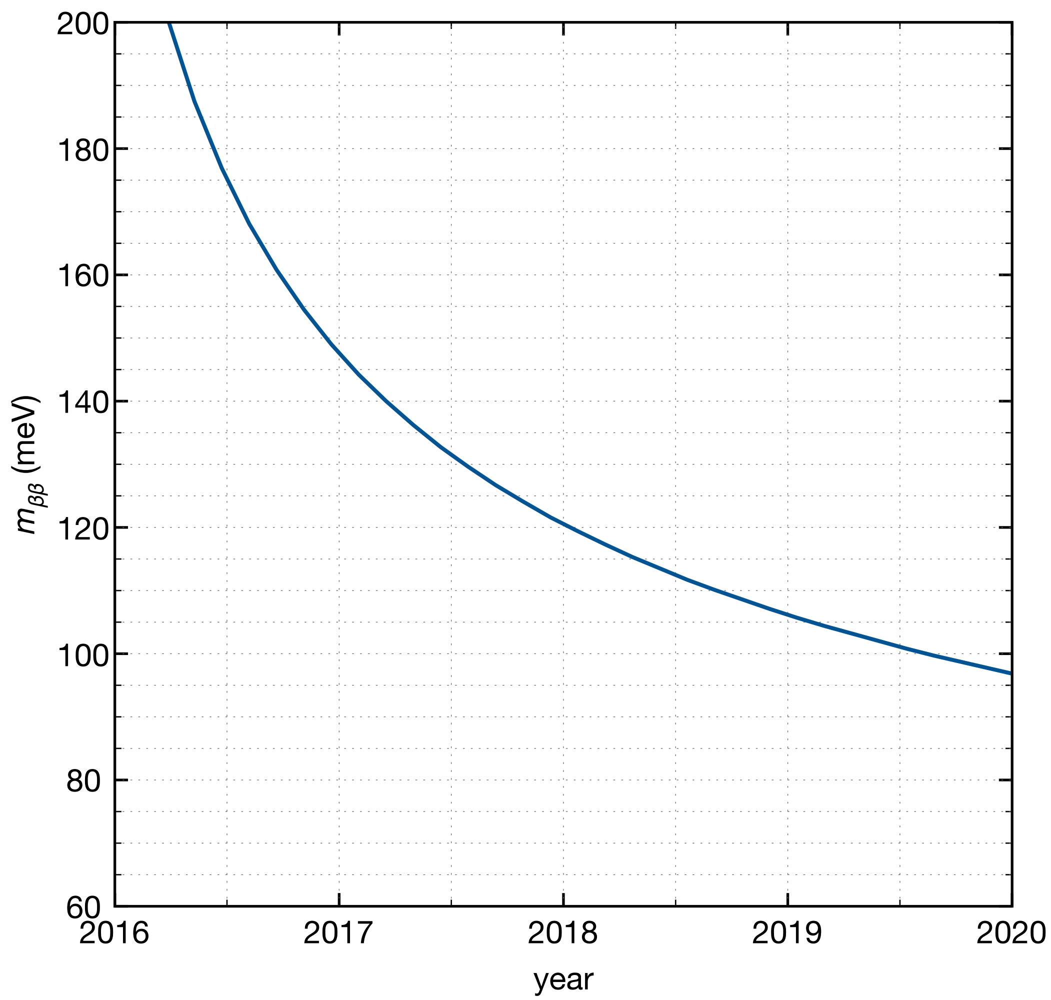
The 2-electron analysis

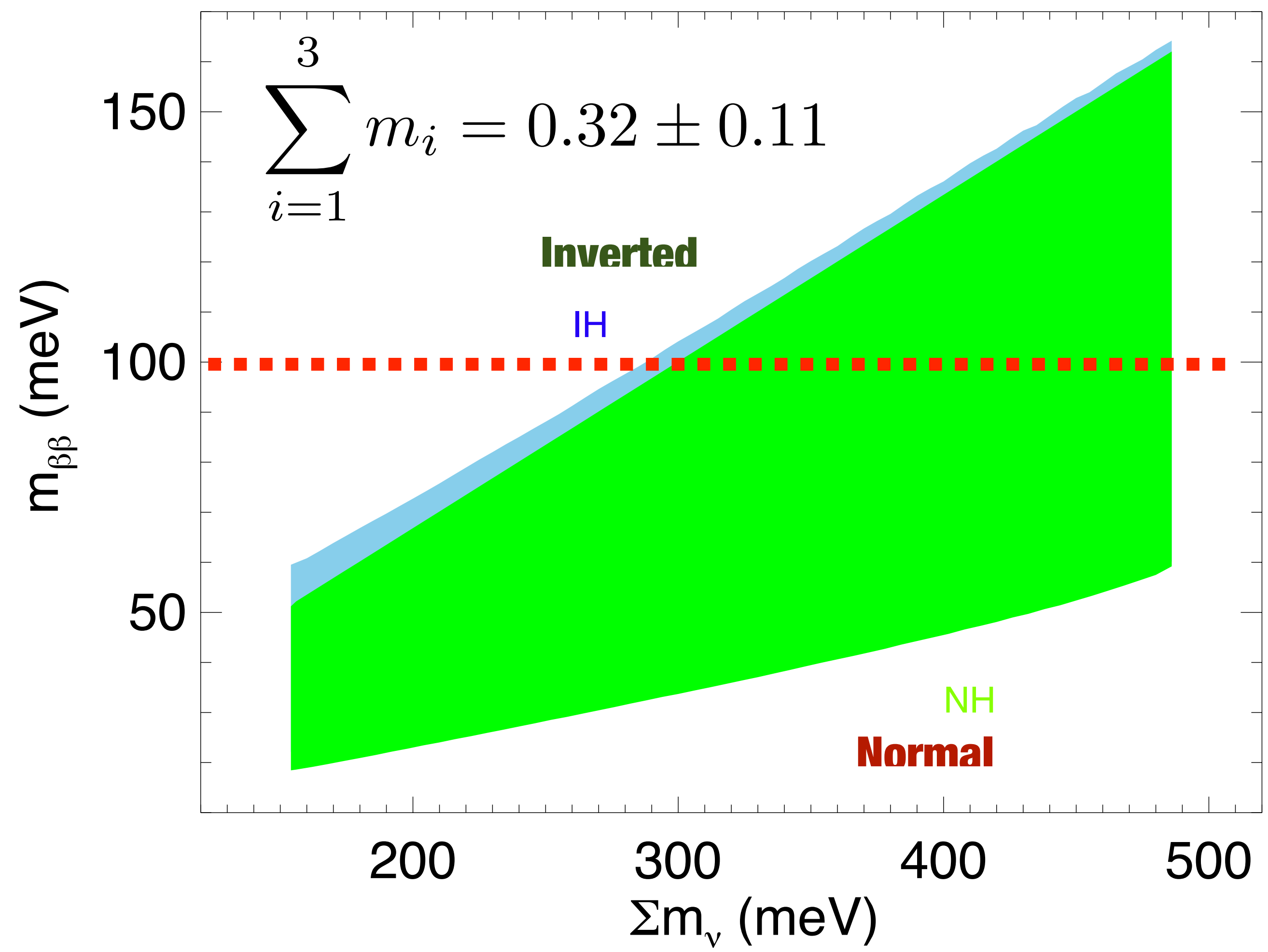
- Effect of the filters (cuts) defining an event with 2 electrons and energy in a ROI of 2σ around $Q_{\beta\beta}$.
- Efficiency for signal ~35% for suppression factors 4-8 x 10^{-7}
- Topology rejection is the product of 1 track x 2 blobs conditions

NEXT 100 expected background

	Activity (Bq)		Rejection Factors		Final rate (ckky)	
	Tl-208	*Bi-214*	*Tl-208*	*Bi-214*	*Tl-208*	*Bi-214*
Dice Boards	4,28E-03	3,21E-03	7,90E-07	8,85E-07	3,047E-05	2,560E-05
PMTs	8,40E-03	3,00E-02	3,30E-07	2,68E-07	2,498E-05	7,244E-05
Field Cage	4,38E-03	1,53E-02	5,30E-07	8,02E-07	2,091E-05	1,107E-04
ICS	1,326E-02	1,105E-01	1,100E-07	8,400E-08	1,315E-05	8,365E-05
Vessel	1,66E-01	5,16E-01	1,10E-08	2,80E-09	1,644E-05	1,301E-05
Shielding Lead	6,266E-01	1,084E+00	2,000E-09	1,000E-10	1,129E-05	9,763E-07
SUBTOTAL	8,23E-01	1,76E+00			1,172E-04	3,063E-04
TOTAL BKGND	2,58E+00				**4,24E-04**	

Physics reach

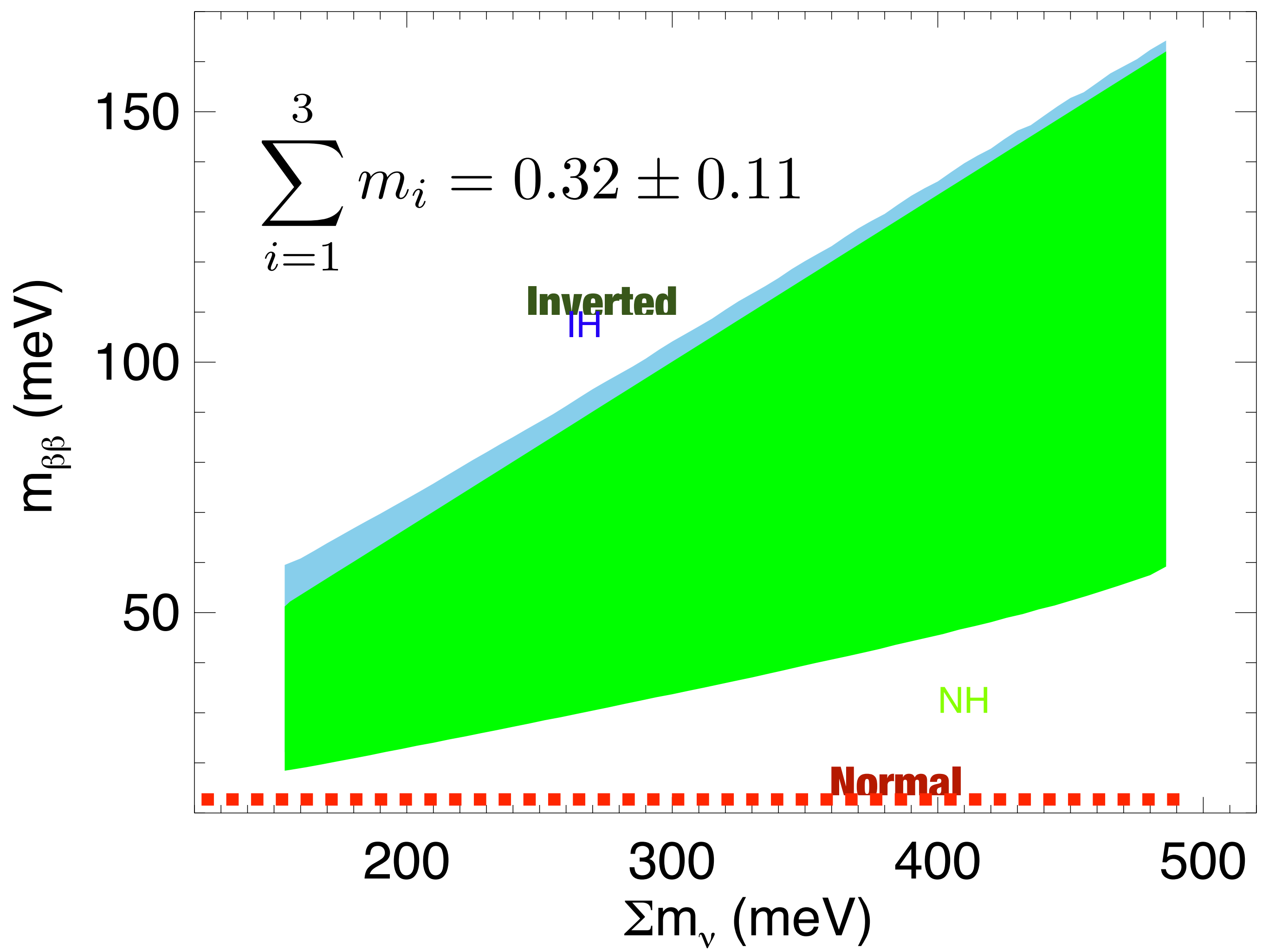




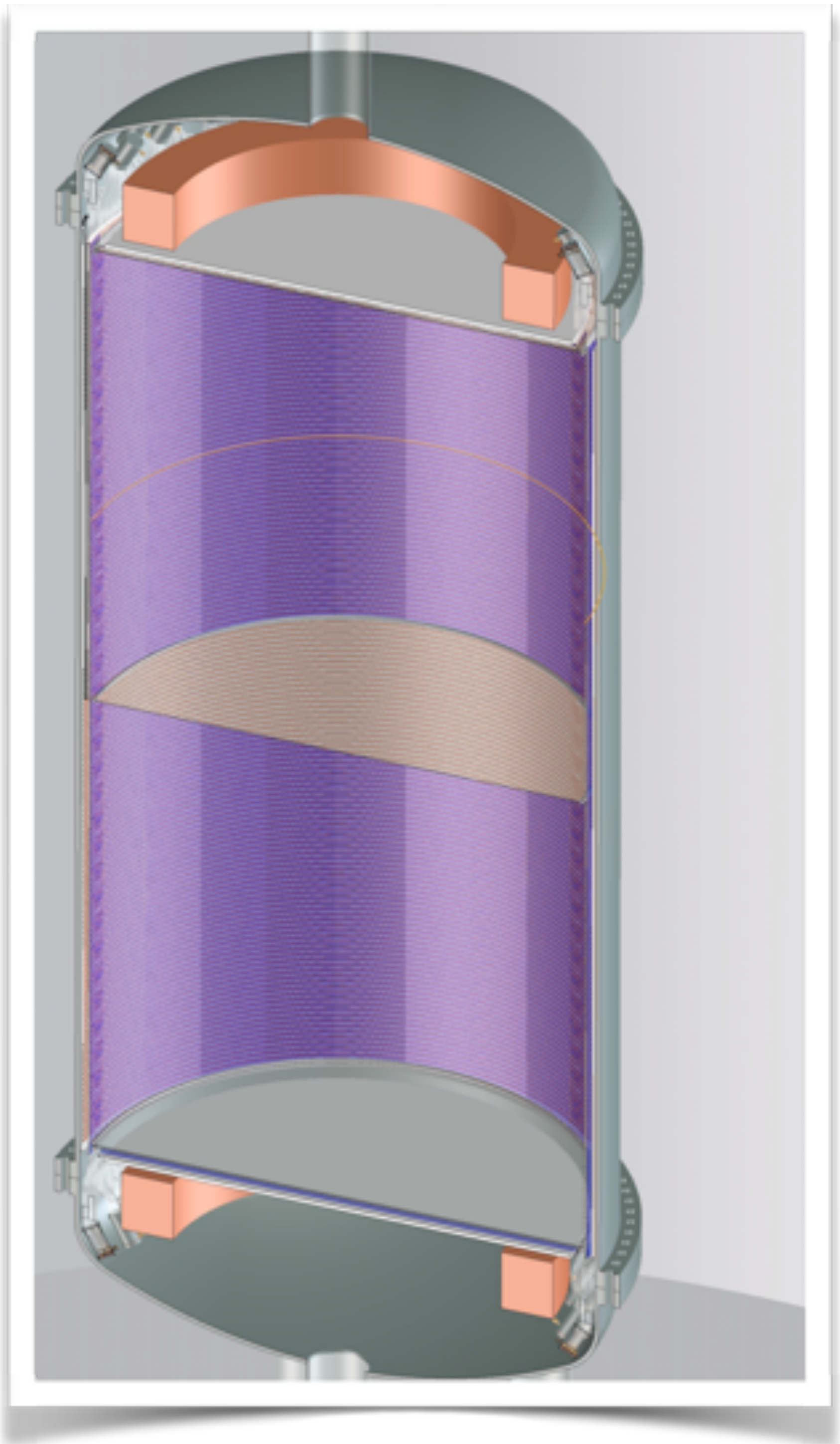
- Reach mv < 100 meV.
- Thus, NEXT has a chance of making a discovery or seeing a hint.

Majorana Gas Instrumented with Xenon

MAGIX

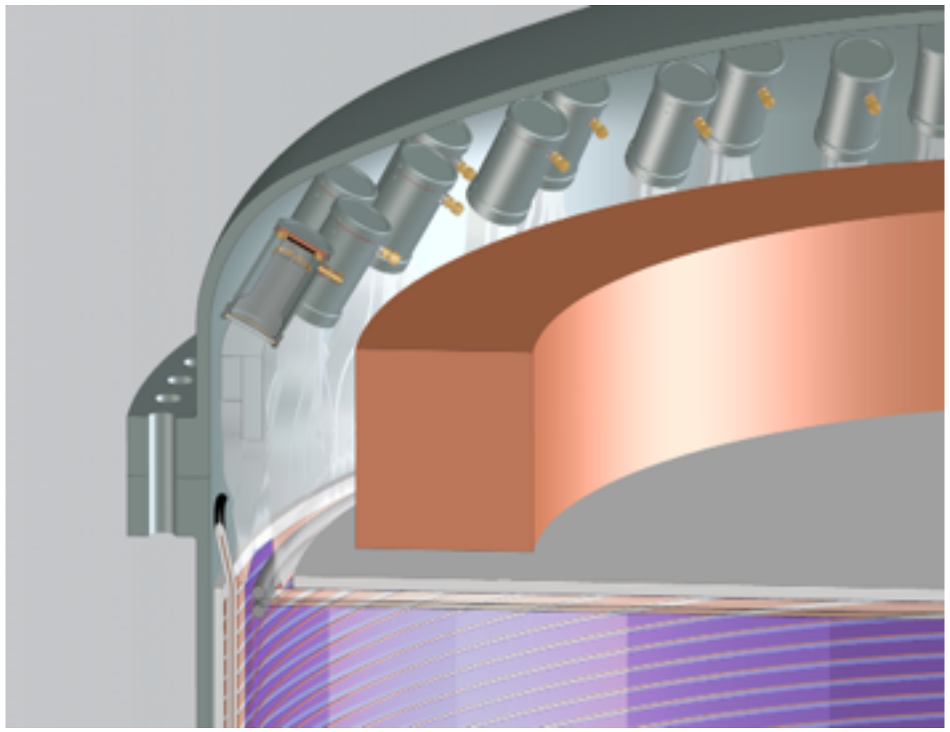


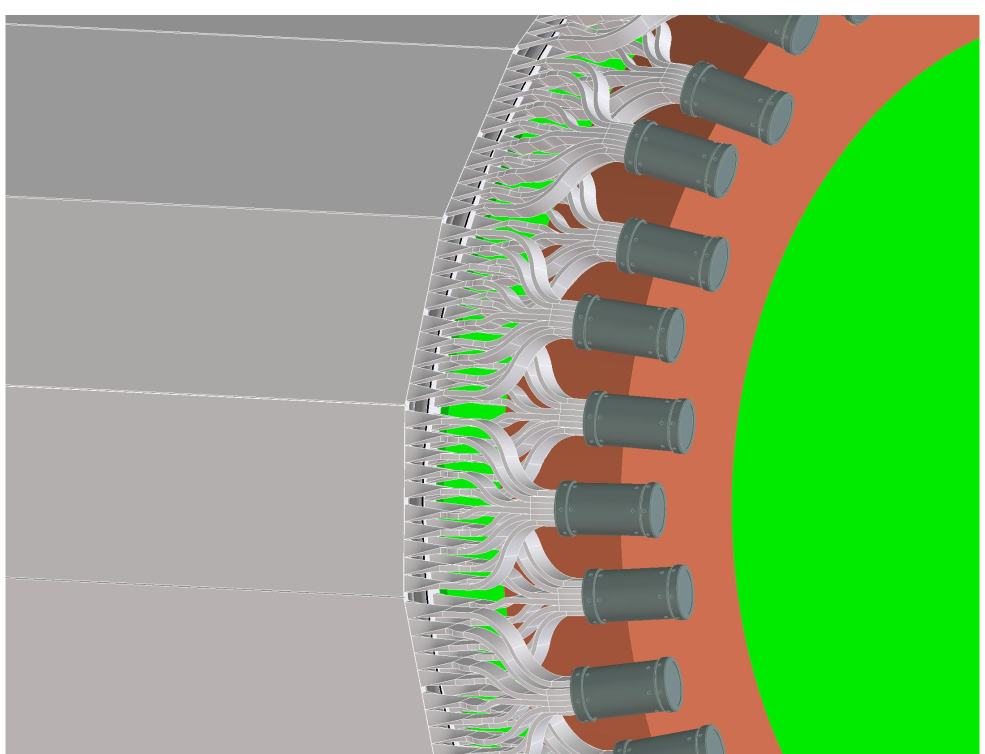
What is MAGIX



- It is a symmetric TPC filled with O(1 ton) of Xenon enriched at 90% in Xe-136 at a pressure of 15 bar
- The drift length is 2 x 2 m (2 ms drift, DEMO measures lifetimes of > 10 ms)
- The TPC radius is about 1 m.
- The active volume is about 12 m^3 (1 ton at 15 bar)
- The event energy is integrated by wavelength shifting light guides surrounding the gas and read by PMTs located outside the fiducial volume.
- The event topology is reconstructed by two planes of radiopure silicon pixels (MPPCs by default).

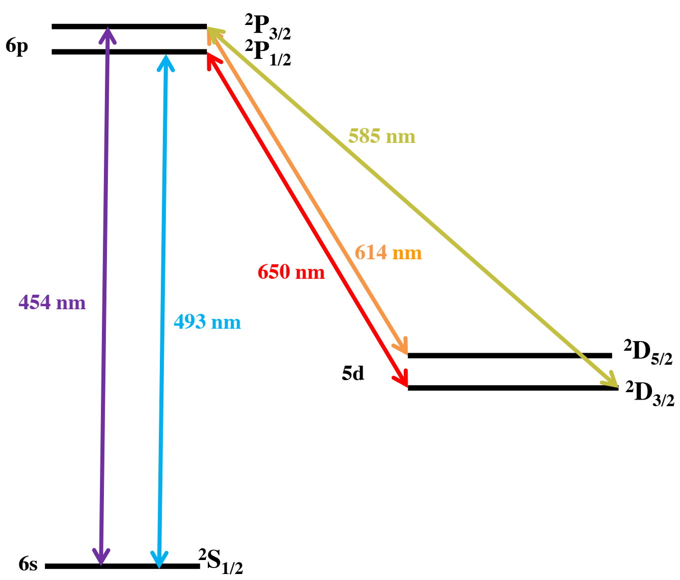
What is MAGIX

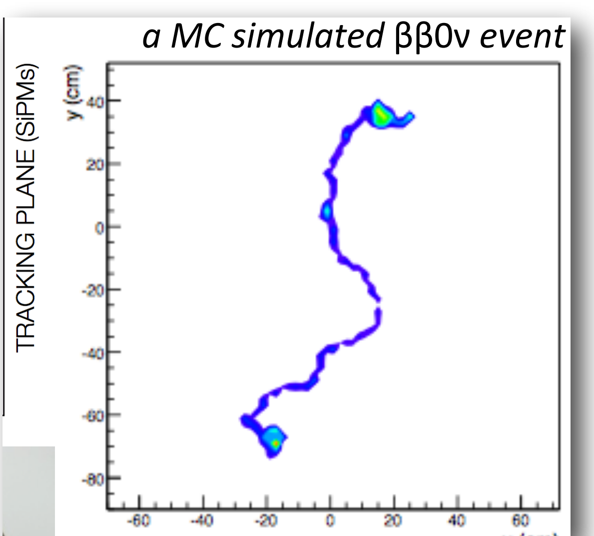


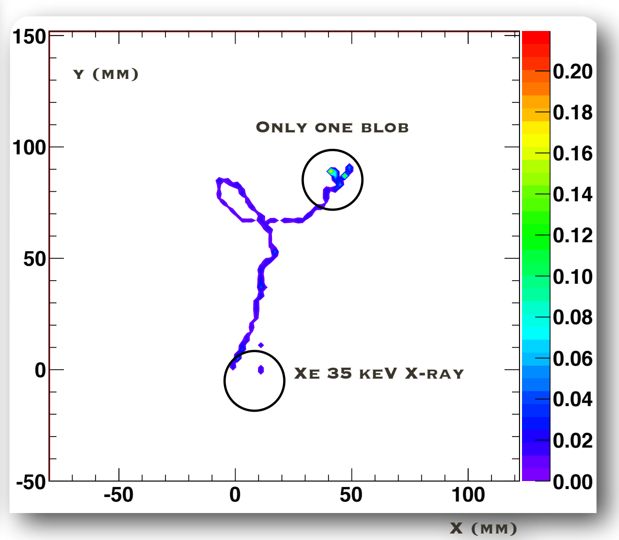


- PMTs outside the fiducial area, shielded by copper. This eliminates one of the three dominating sources of background.
- Detector inside a water tank with better stopping power than lead may allow to reduce the thickness of ICS.
- Gas additives? TMA could reduced lateral diffusion (better tracking) and improve resolution (penning effect).
- Economy of scale automatically yields a factor ~2.5 background reduction.

The MAGIC of MAGIX

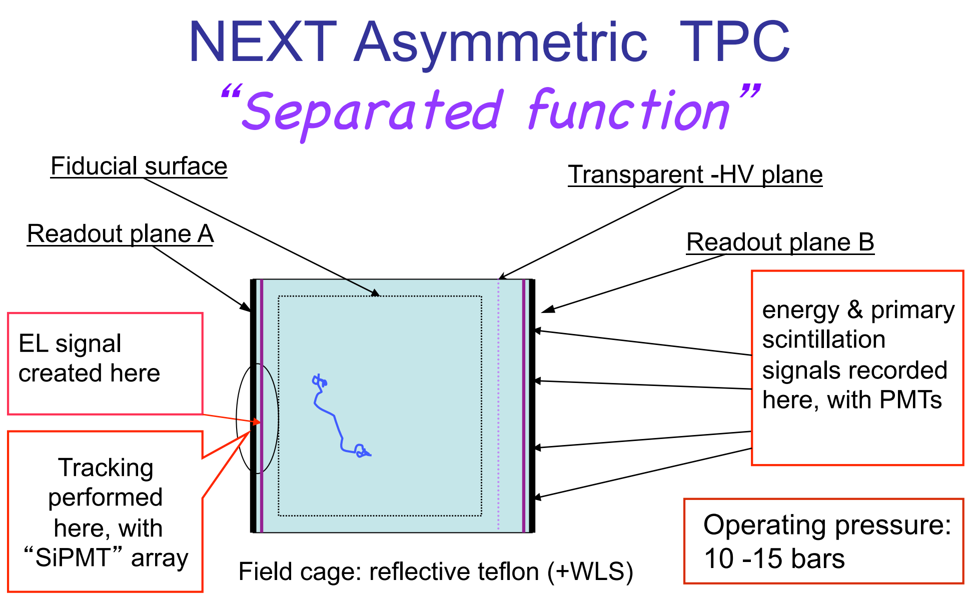


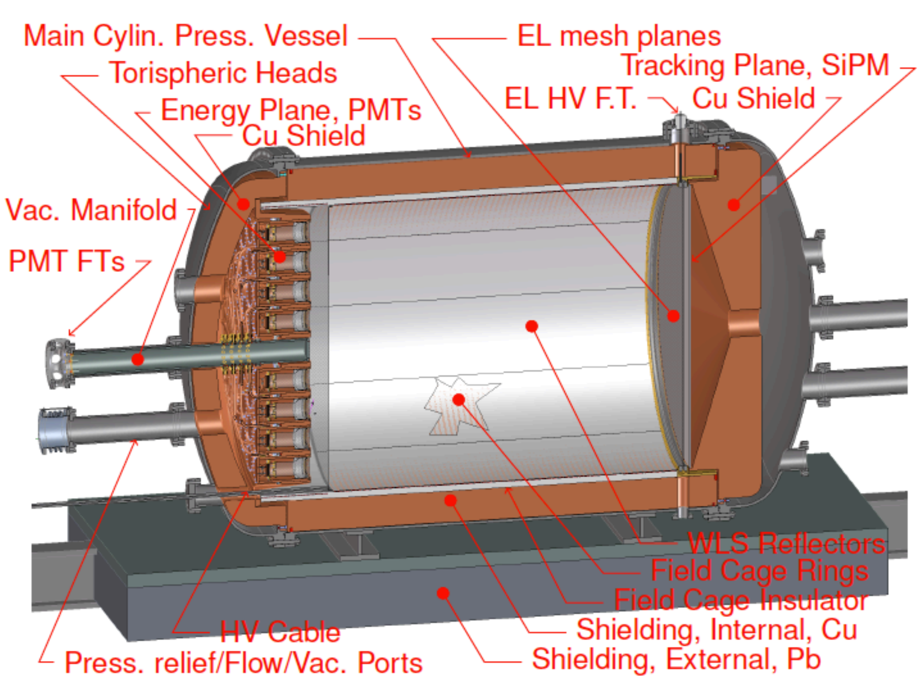




- A HPXe TPC with a mass in the range of the ton can explore the inverted hierarchy, reaching ~20 meV and operating as a virtually background-free detector.
- The topological signature can be enhanced by reducing lateral diffusion (TMA) among other possibilities.
- Ba tagging may also be available in gas.
- Overall MAGIX may be the ultimate detector to discover the Majorana nature of the neutrino.

Dave’s 5 cents to NEXT and MAGIX





- Invented the TPC.
- Proposed the use of EL as the only valid way to achieve energy resolution.
- Invented the SOFT concept.
- Proposed the concept of “dual TPC” (same apparatus, different configurations for DM and bb0nu)
- Proposed the use of TMA to improve the response of both bb0nu and DM mode
- Fundamental contributions to design and R&D
- And most importantly he has taught us the secret of….

Physics as a fountain of eternal youth

http://www.jotdown.es/2012/09/david-nygren-y-alessandro-bettini-the-physics-as-fountain-of-eternal-youth/